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Title:	Applications of seismic threshold monitoring at an Antarctic glacier
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Applications of seismic threshold monitoring at an Antarctic glacier

Chris Carr, 26 Aug 2021

Photo: Chris Carr

Collaborators:
Erin Pettit, Oregon State University
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Funding & equipment:
UNAVCO
NSF
IRIS PASSCAL POLAR PROGRAM

Fieldwork: Jess Badgeley, Cece Mortenson, Erin Pettit, Susan Detweiler, Jason Hebert Jenn Erxleben, Thomas Nylen, + USAP, USAF personnel


Photo: Thomas Nylen


Photo: Jess Badgeley


Photo: Anna McKee


Photo: Pat Dryer


Photo: Ted Scambos

Photo: Cece Mortenson

Challenges in Arctic seismic monitoring

- Geophysical waveforms collected from Arctic regions provides data required for monitoring global security targets

- Some seismic instruments deployed on Scandinavian and Greenlandic sites provide waveform data, but these installations include specific challenges:
  - Sea ice and glacial ice generates waveform interference
  - Meltwater generates narrowband interference, resembling tonal noise

- I will specifically discuss how to quantify the performance of some sensor installations at high latitudes

Challenges in the cryosphere

Cryosphere responds to:

- multi-year climate change
- seasonal variability
- diurnal variability
- transient weather events

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M_L 2.0 lake-associated icequakes

Kavanaugh et al., 2018

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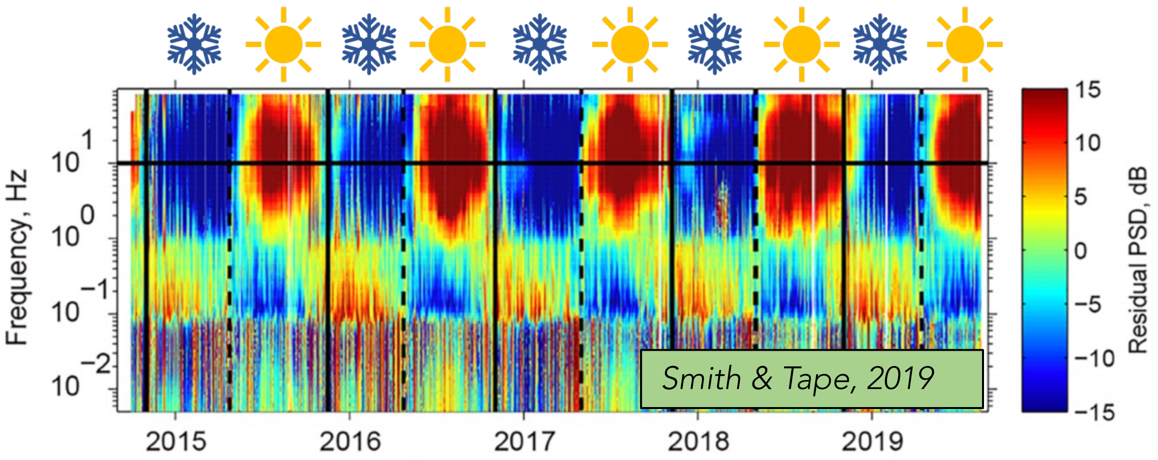
River ice presence/absence influences river noise



Smith & Tape, 2019

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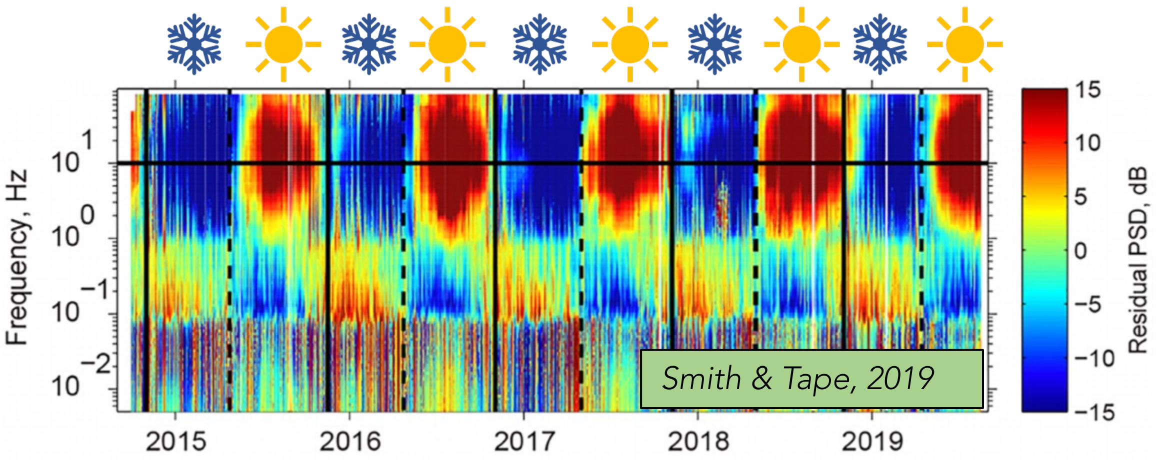
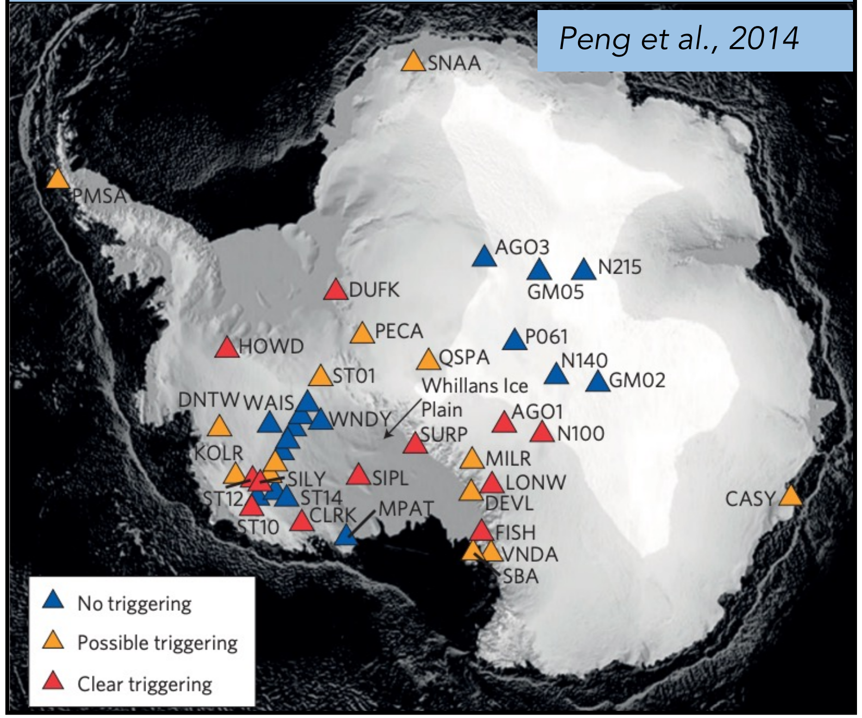


Smith & Tape, 2019

Antarctic icequakes triggered by the 2010 Maule earthquake in Chile



Peng et al., 2014

Challenges in the cryosphere

Cryosphere responds to:

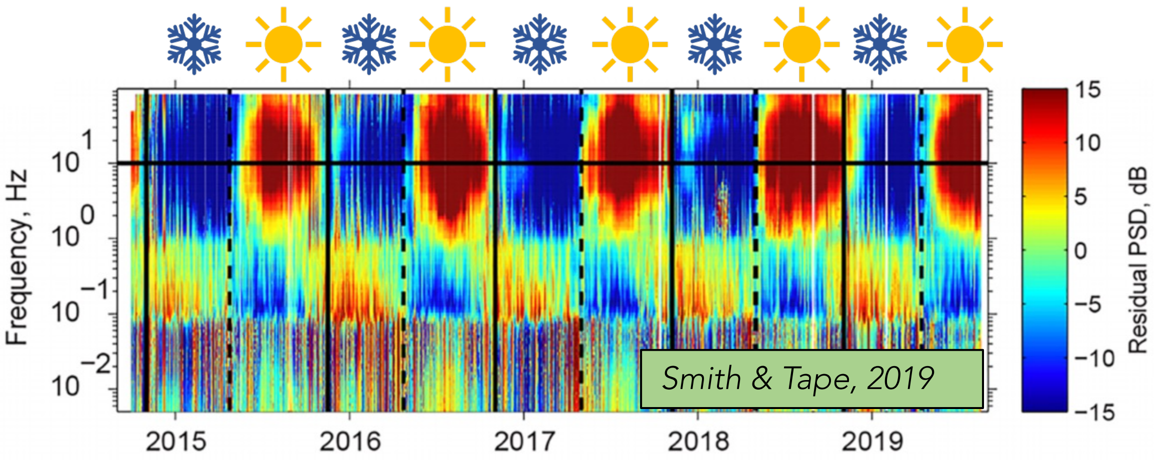
- multi-year climate change
- seasonal variability
- diurnal variability
- transient weather events

How does the changing cryosphere impact our detection of small seismic sources?

M_L 2.0 lake-associated icequakes

Kavanaugh et al., 2018

River ice presence/absence influences river noise



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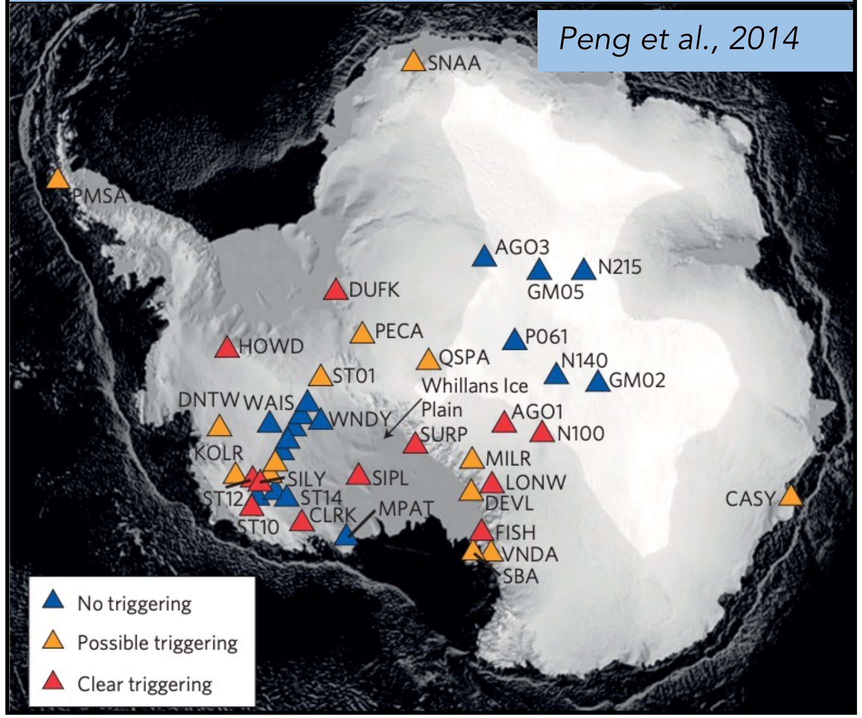

How can we quantify false negatives?

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One tool: waveform infusion (aka waveform injection)

- General "recipe", customizable for different data types & detection algorithms
- Applications:
  - Compare performance of multiple detectors
  - Track temporal variability in detection capability
- Toy example on next slide uses 5 minutes of single-channel data:

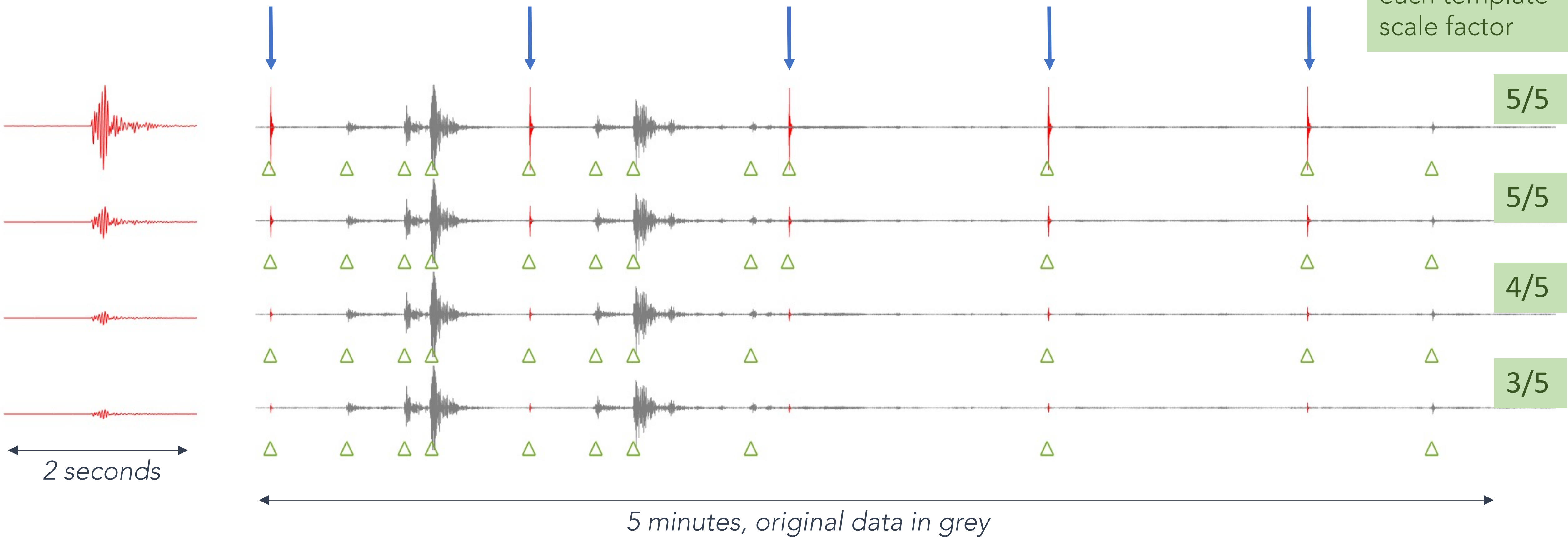
- A simple STA/LTA detector identifies signals (△) embedded in noise

Waveform infusion recipe

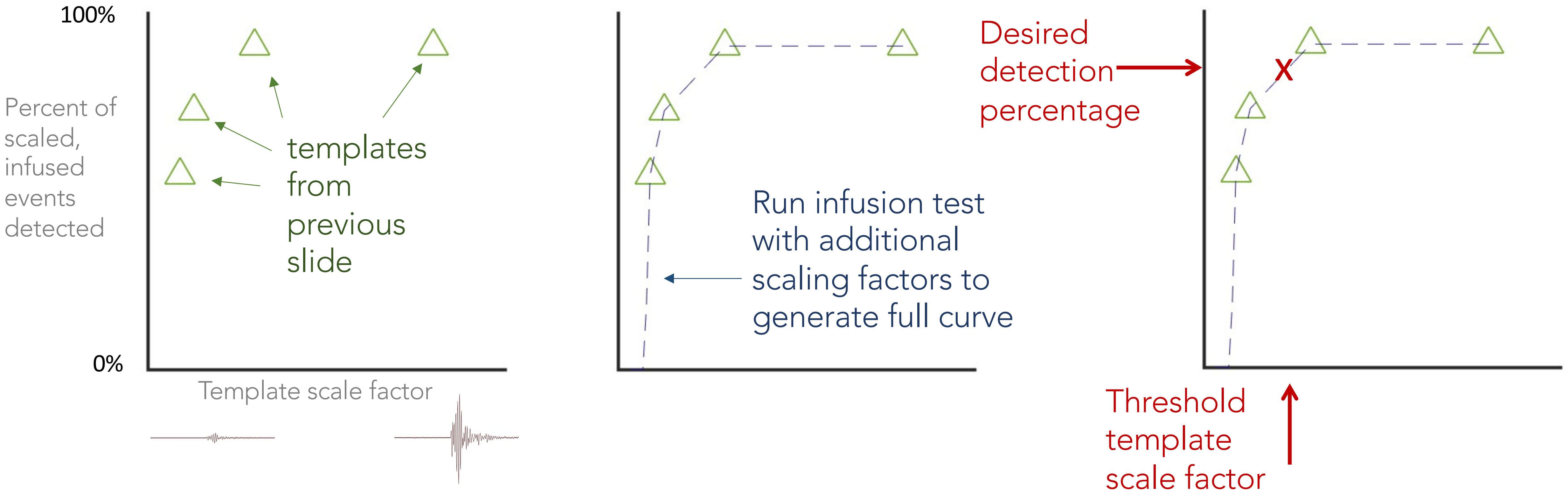
1. Scale an event

2. Add to original data at known timestamps

3. Run detector, count how many infused events detected for each template scale factor



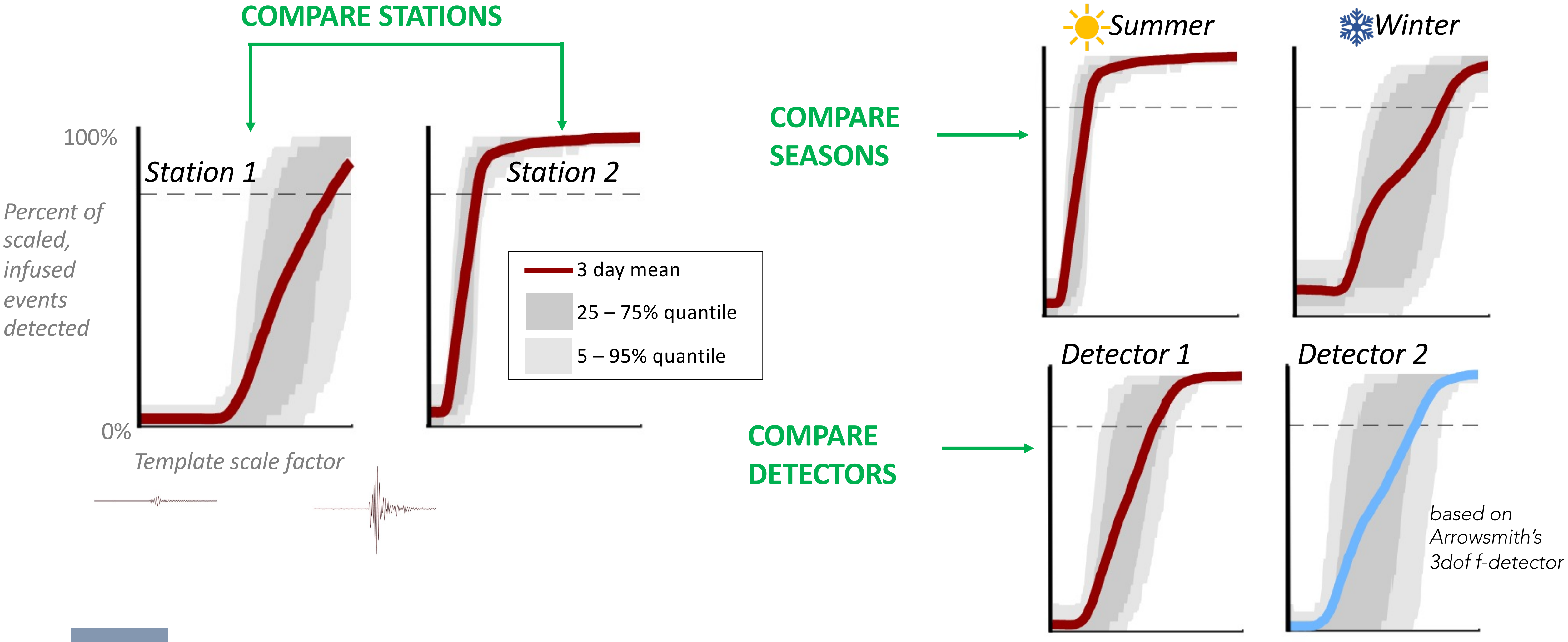
Test a range of scaling factors for infused template, determine threshold size **



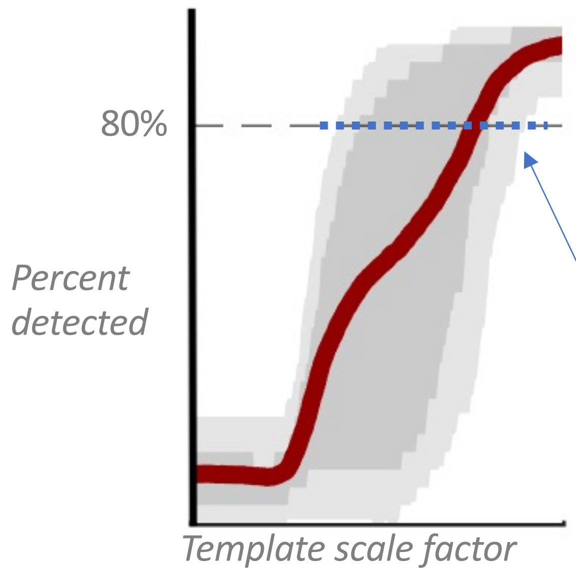
**** Repeat the process for each block of time****

(scale template, infuse, detect, generate curve, find threshold)

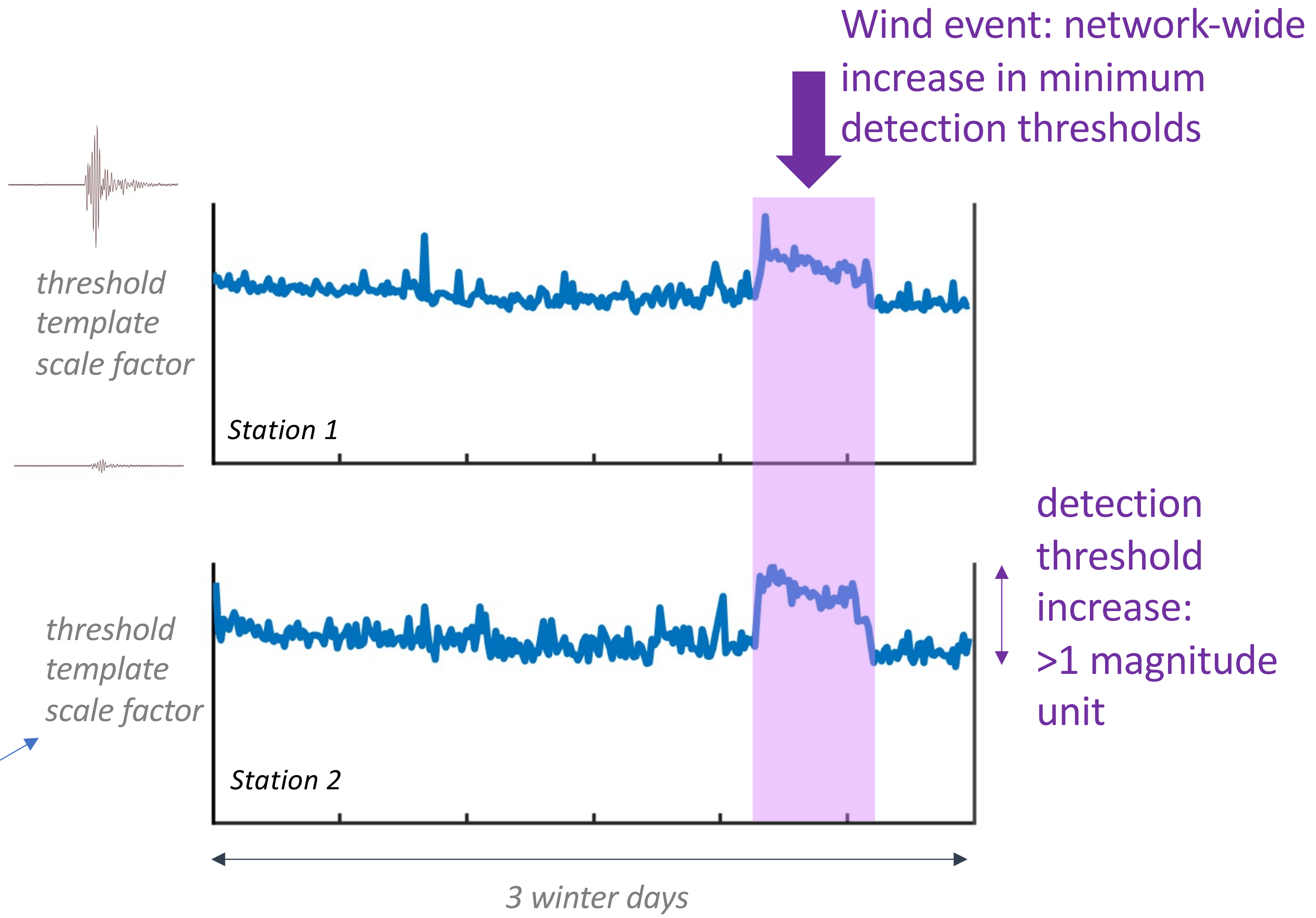
Application: compare detection performance



Application: temporal variability in detection thresholds



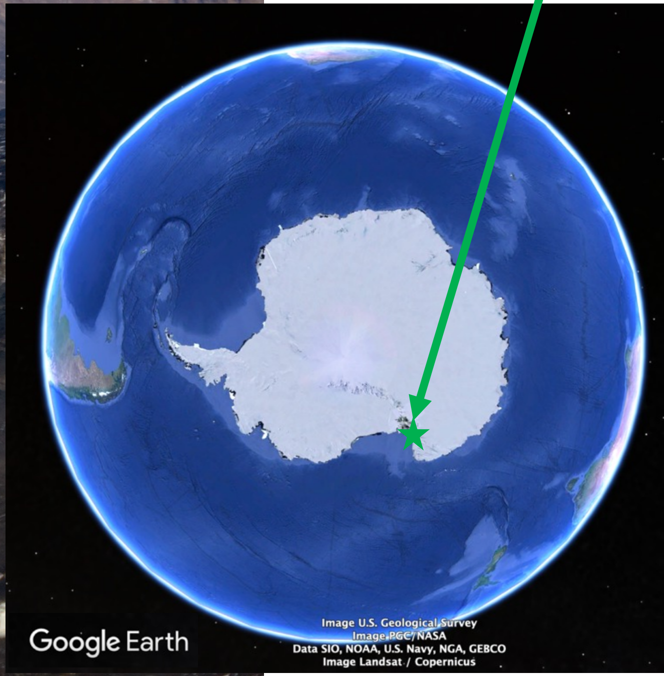
Plot
threshold template scale factor
as a time series



Modified from Carr et al., 2020, Journal of Glaciology

Blood Falls & Taylor Glacier, Antarctica

McMurdo
Dry Valleys



Blood Falls

winter event

Photo: Peter Rejcek, NSF

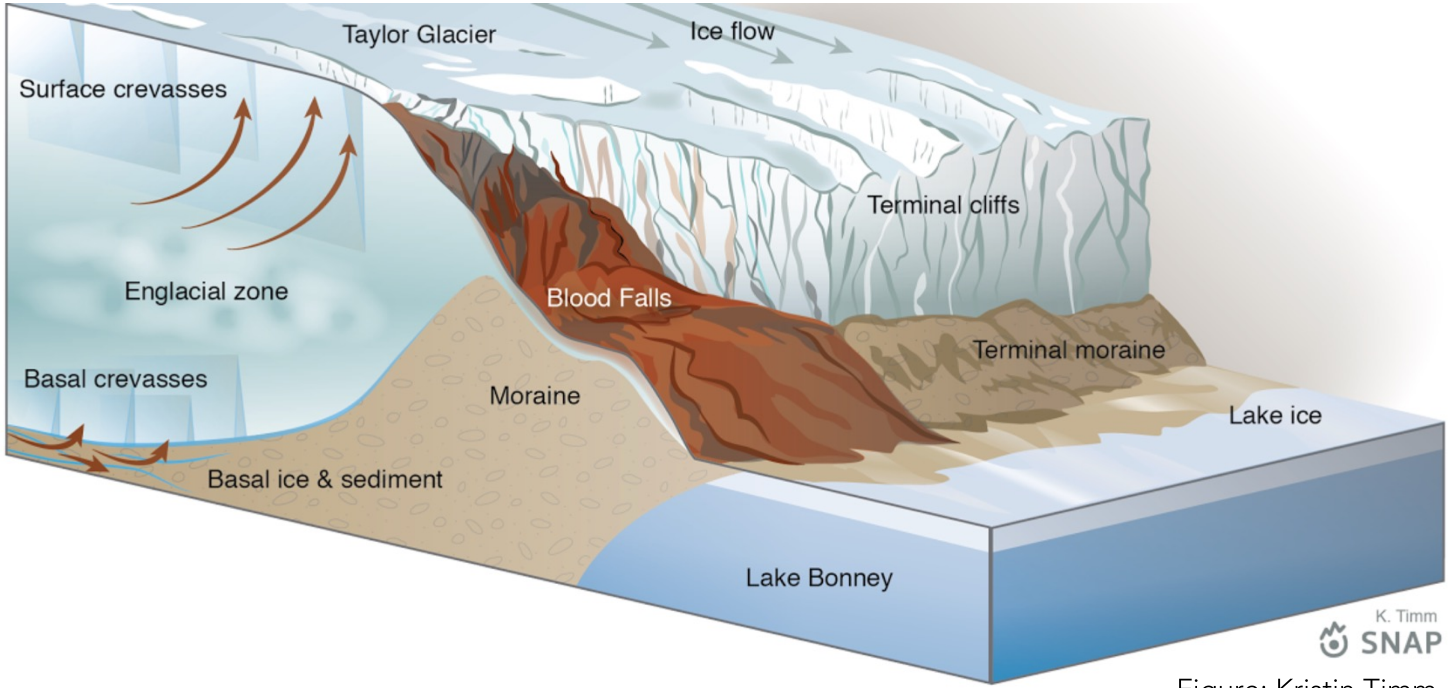
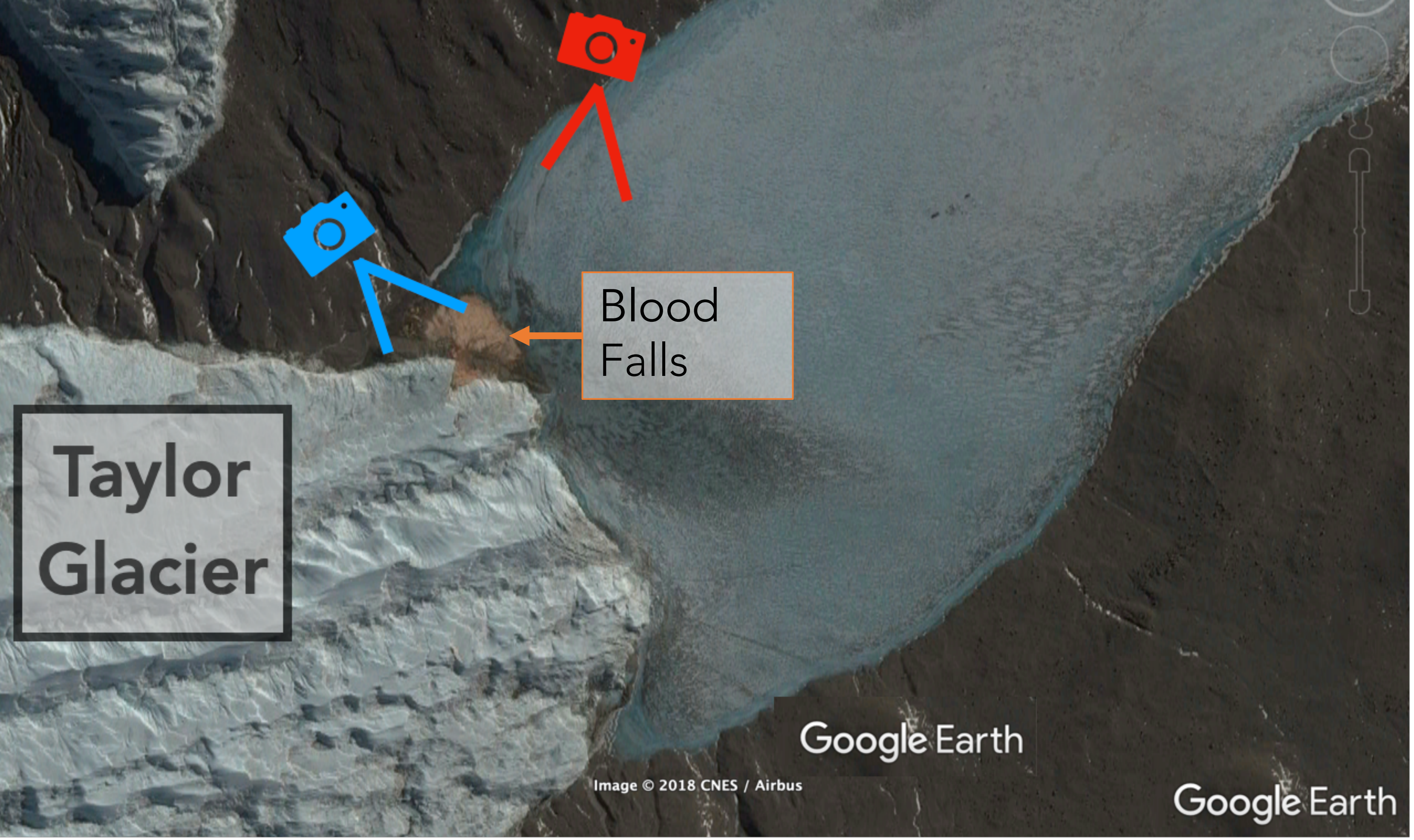


Figure: Kristin Timm


Blood
Falls
Taylor
Glacier
Google Earth
Image © 2018 CNES / Airbus
Google Earth

Photos from 2 cameras show a brine release event during winter 2014

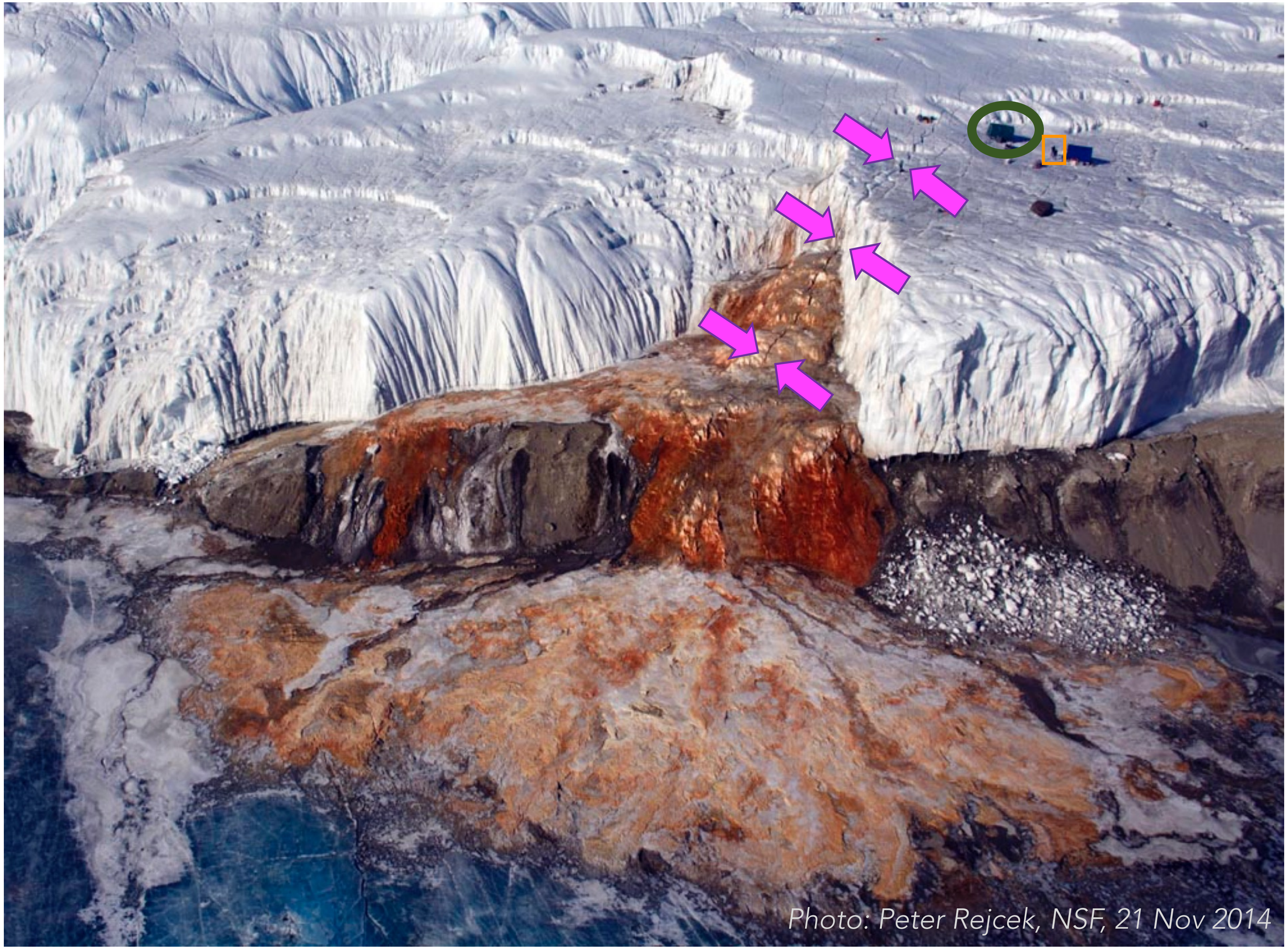


Photo: Peter Rejcek, NSF, 21 Nov 2014

large cracks in glacier surface

tent

2 people

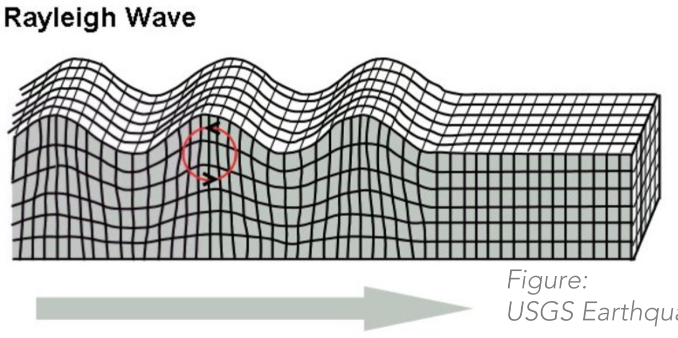
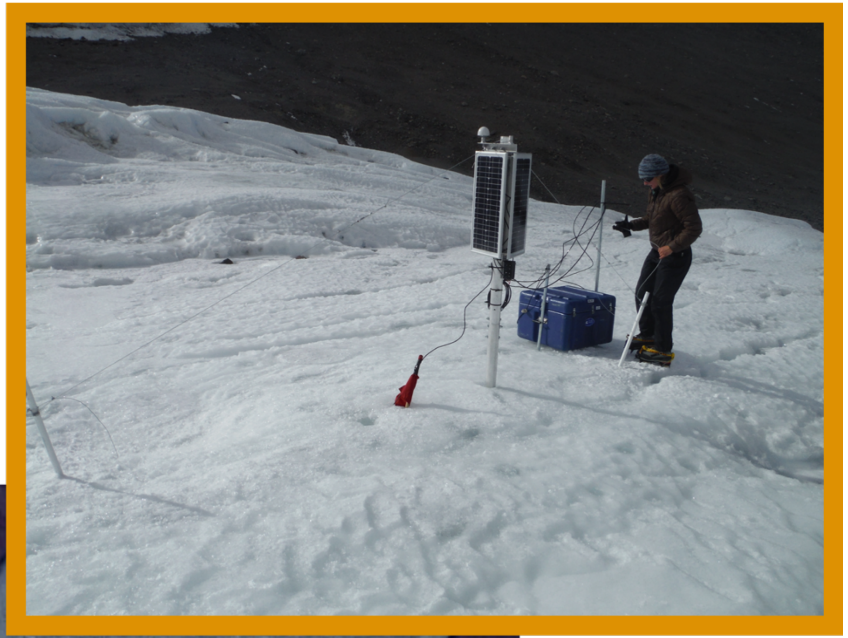
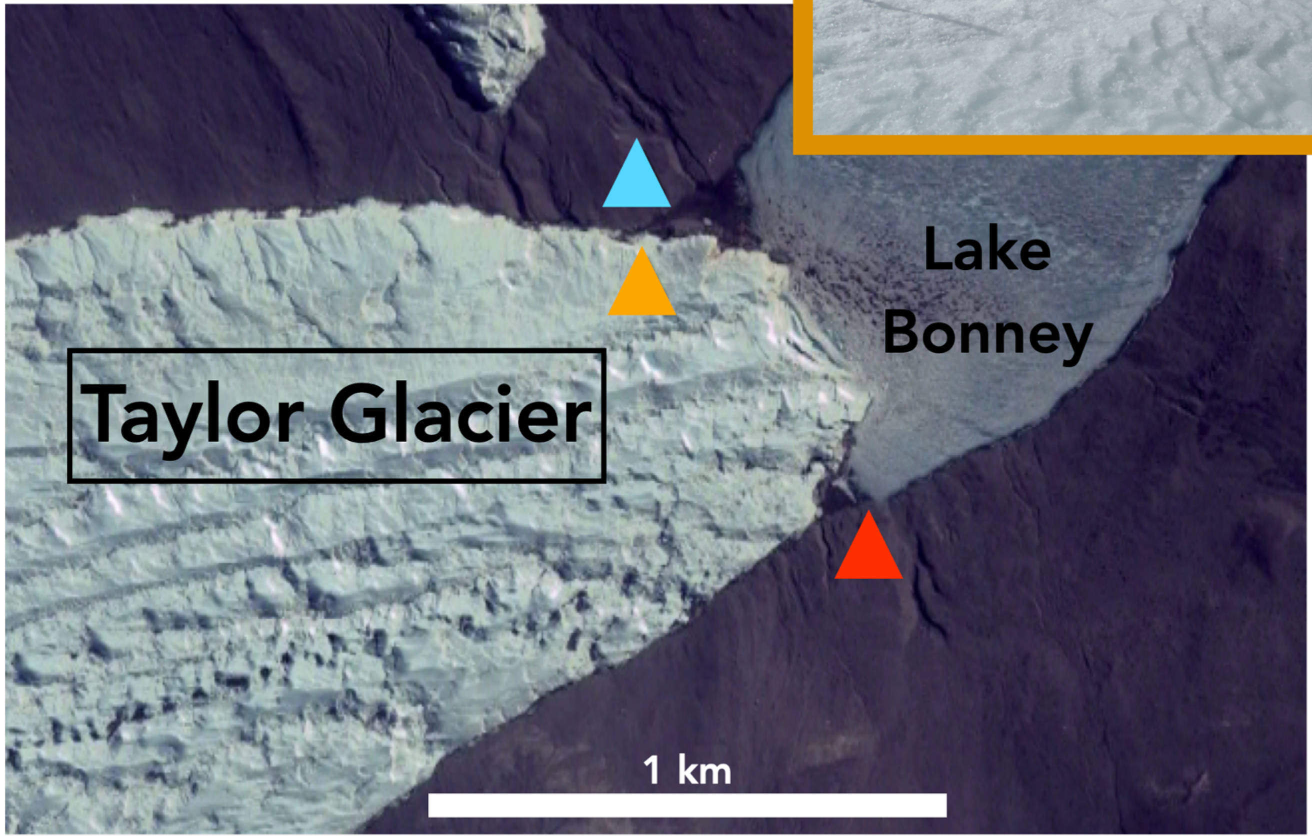


Figure: USGS Earthquake Glossary

*Retrograde,
elliptically polarized motion,
decays rapidly with depth*

Nov 2013 — Jan 2015:
3 seismic stations

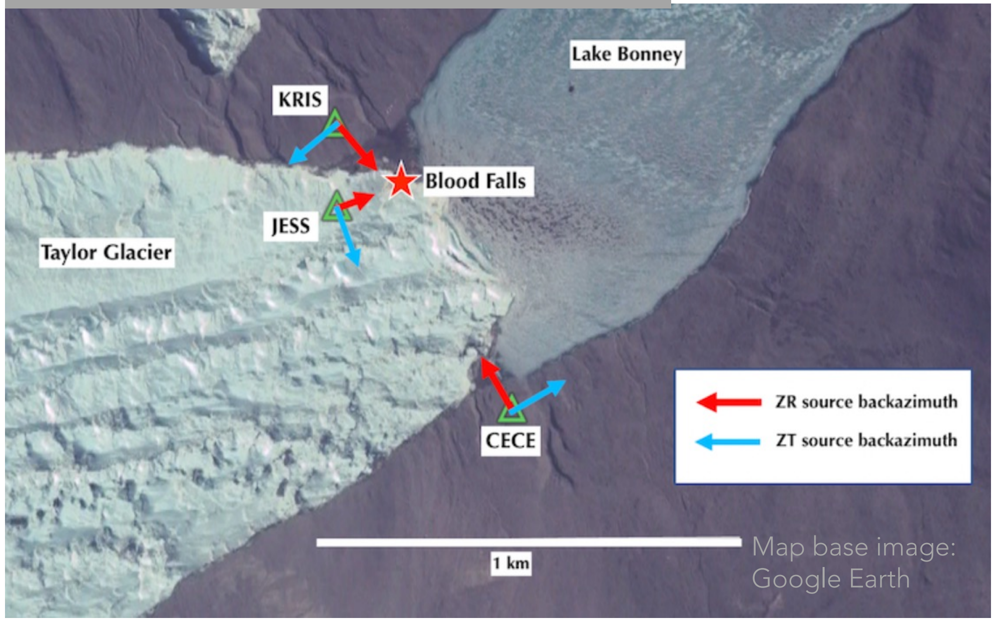




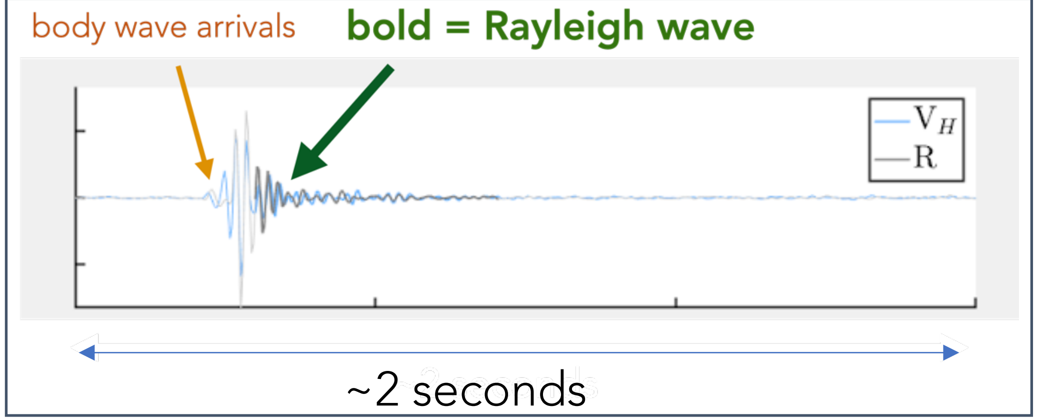
Photos: Chris Carr

Map base image: Google Earth

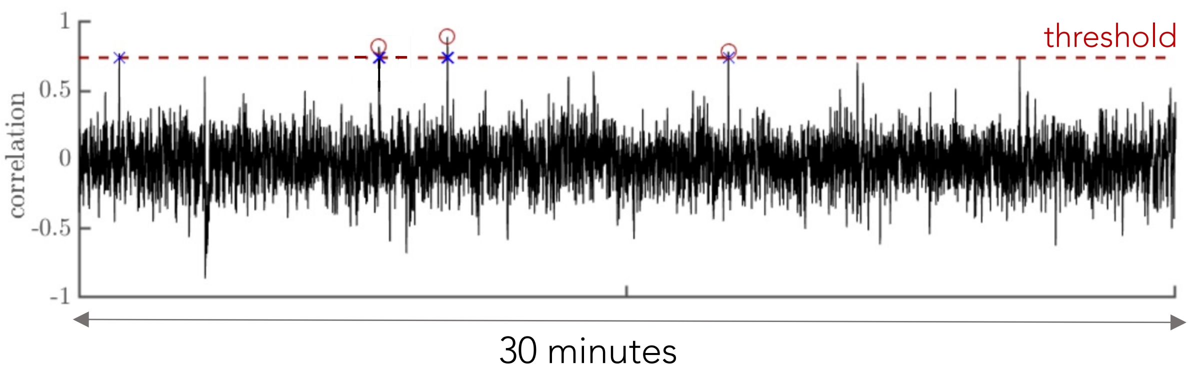
1. Rotate into Blood Falls reference frame



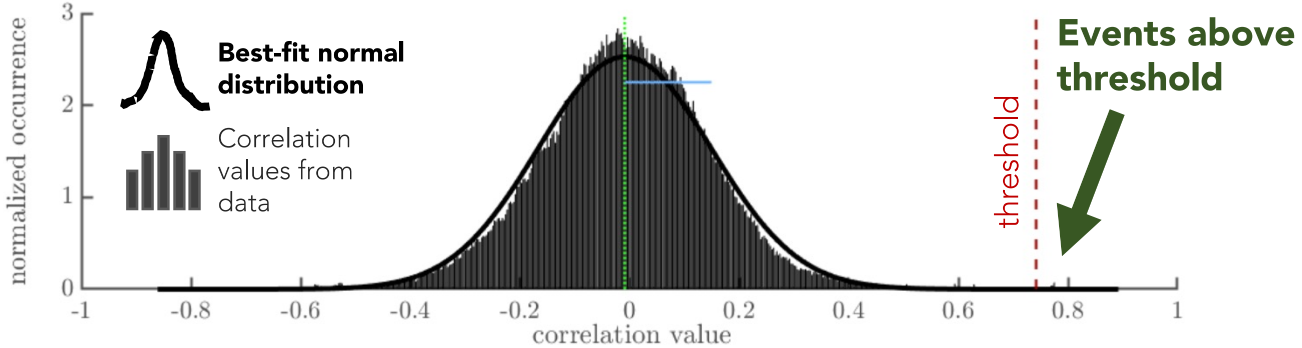
2. Phase shift vertical channel (V_H)



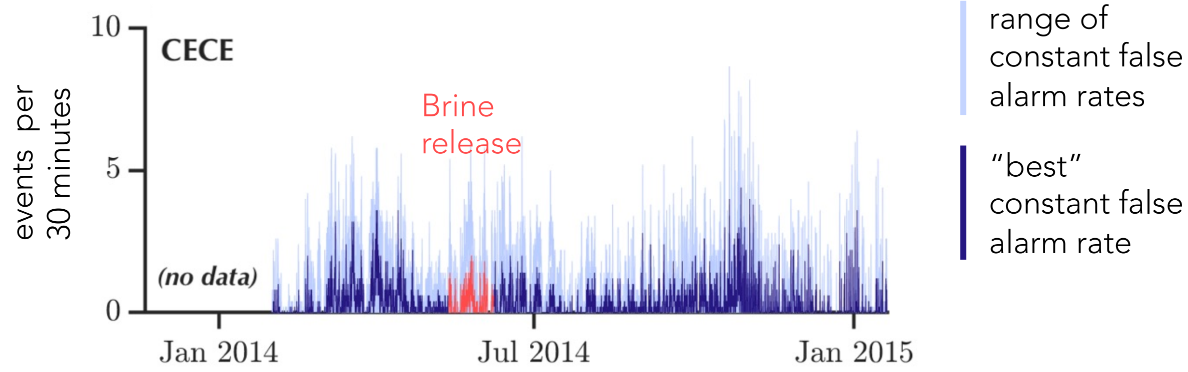
3. Calculate correlation values



4. Find best-fit normal distribution and threshold



5. Construct time series of event counts



Modified from Carr et al., in review, JGR-Earth Surface

What size events are we detecting?

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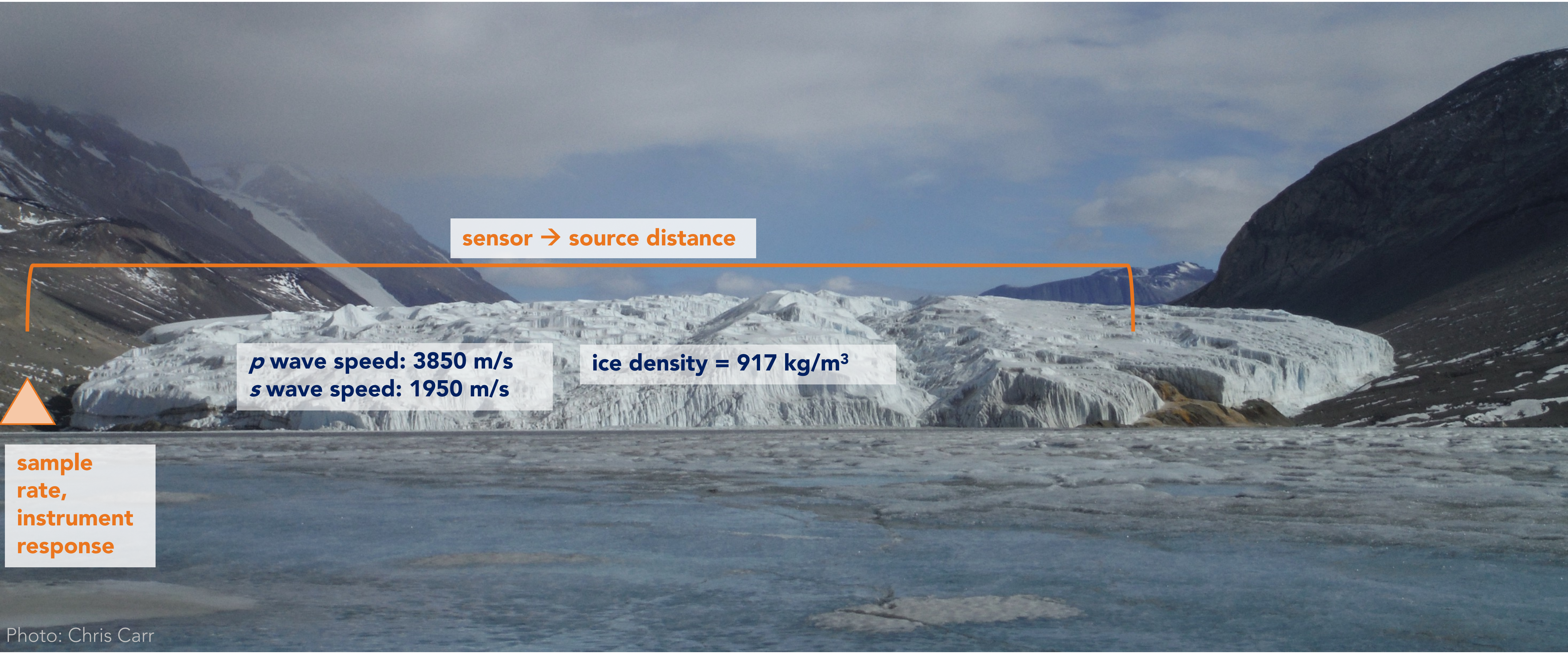

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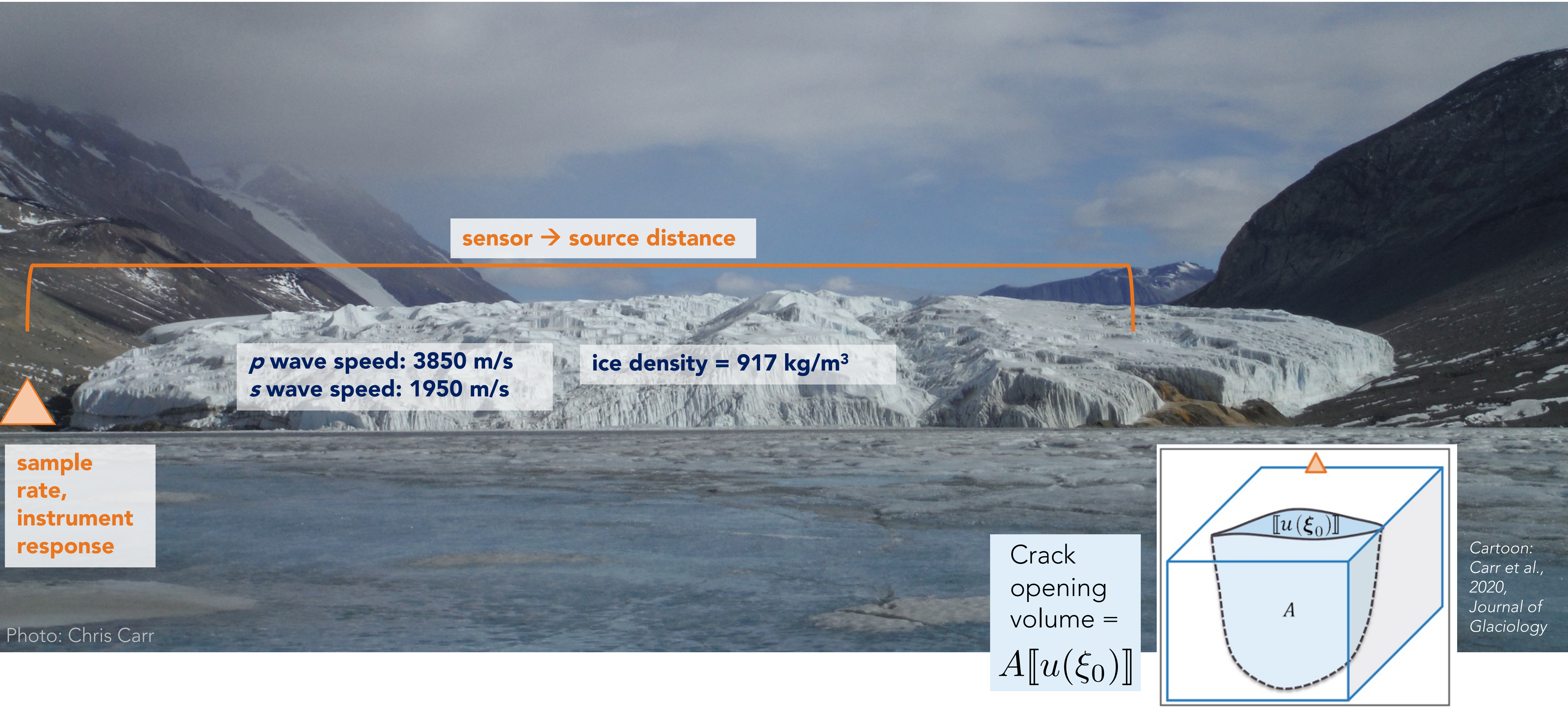
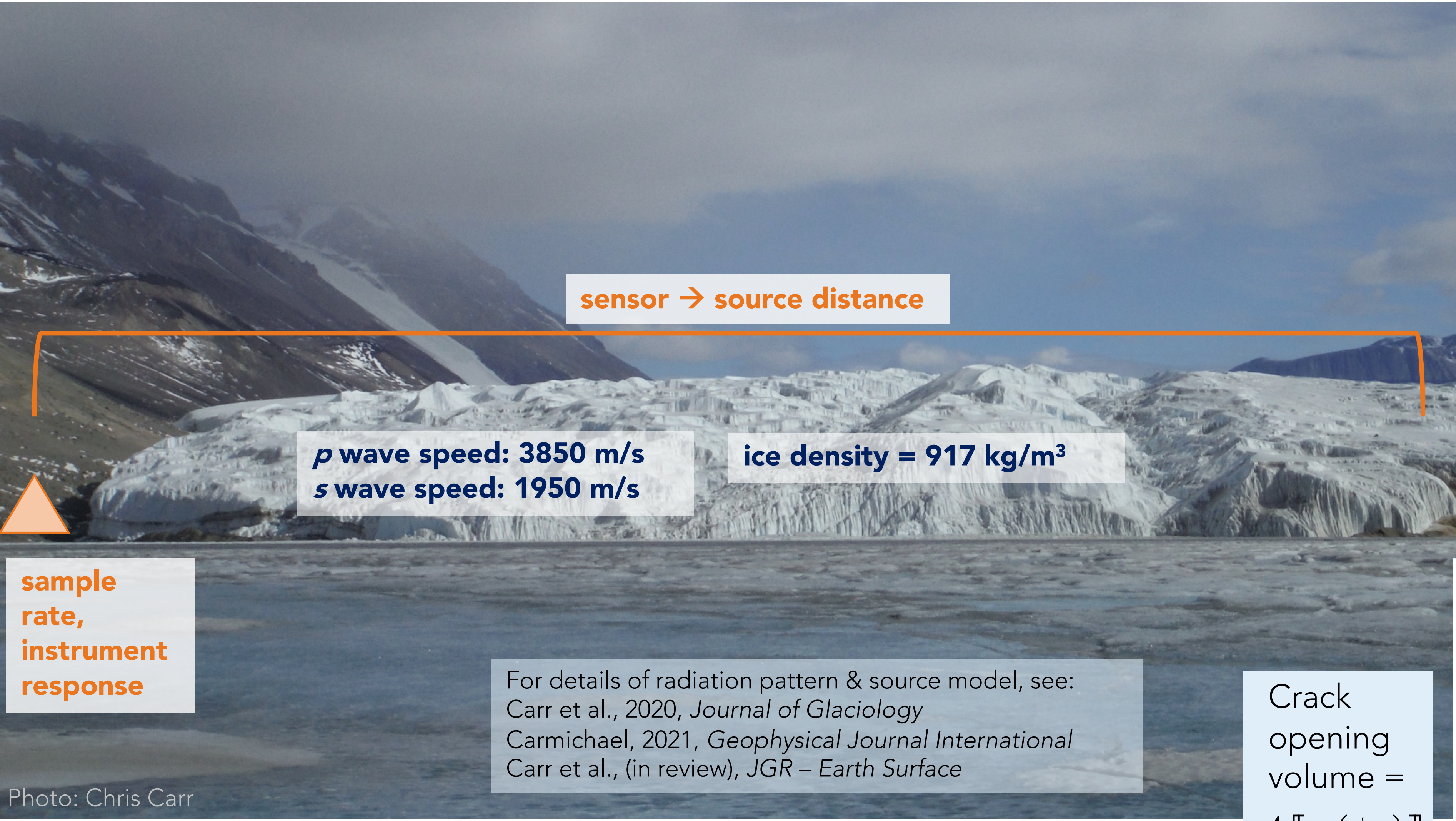


Crack opening volume = $A[\![u(\xi_0)]\!]$

Cartoon: Carr et al., 2020, Journal of Glaciology

Crack opens instantaneously, template volumetric change = 0.1 m^3

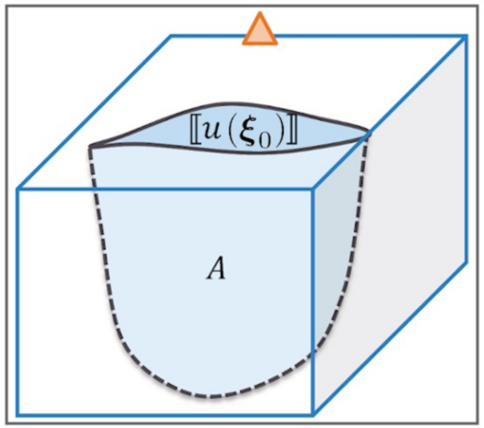
What size events are we detecting?



For details of radiation pattern & source model, see:
Carr et al., 2020, *Journal of Glaciology*
Carmichael, 2021, *Geophysical Journal International*
Carr et al., (in review), *JGR – Earth Surface*

Photo: Chris Carr

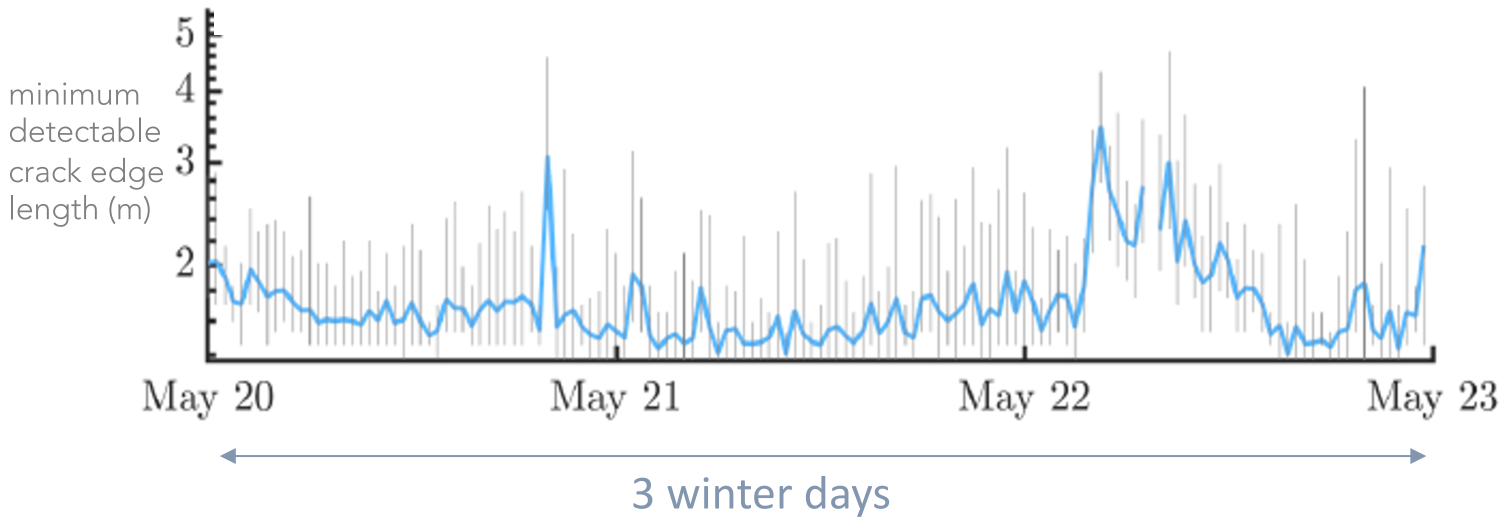
Crack opening volume = $A[\![u(\xi_0)]\!]$



Cartoon: Carr et al., 2020, Journal of Glaciology

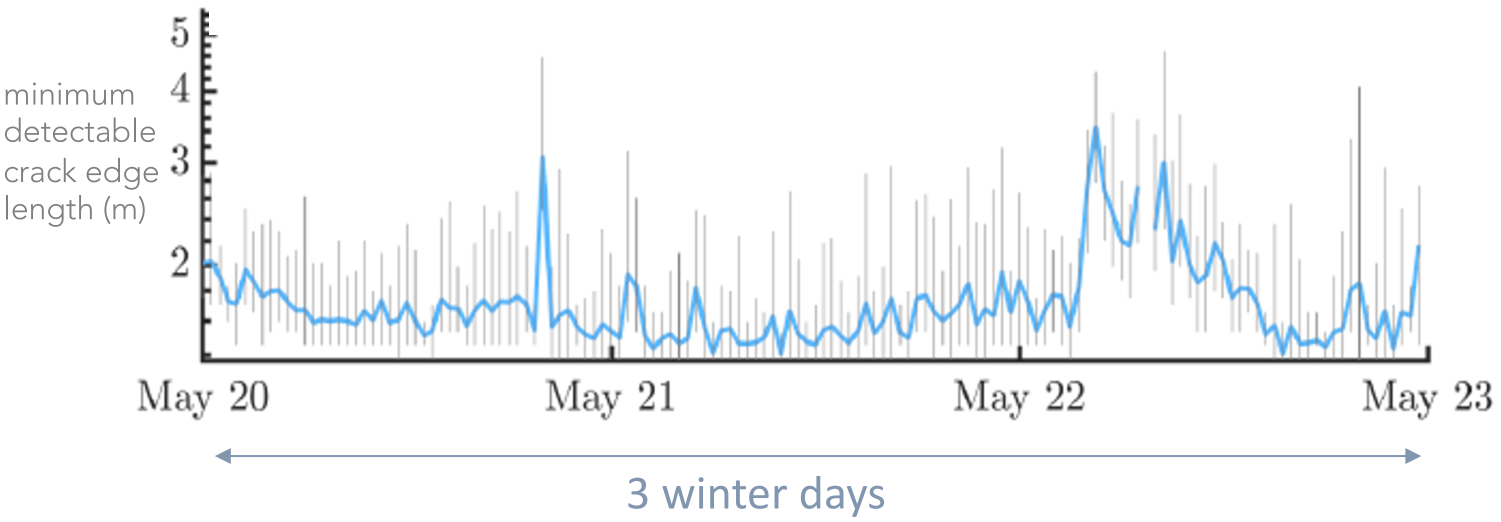
Crack opens instantaneously, template volumetric change = 0.1 m^3

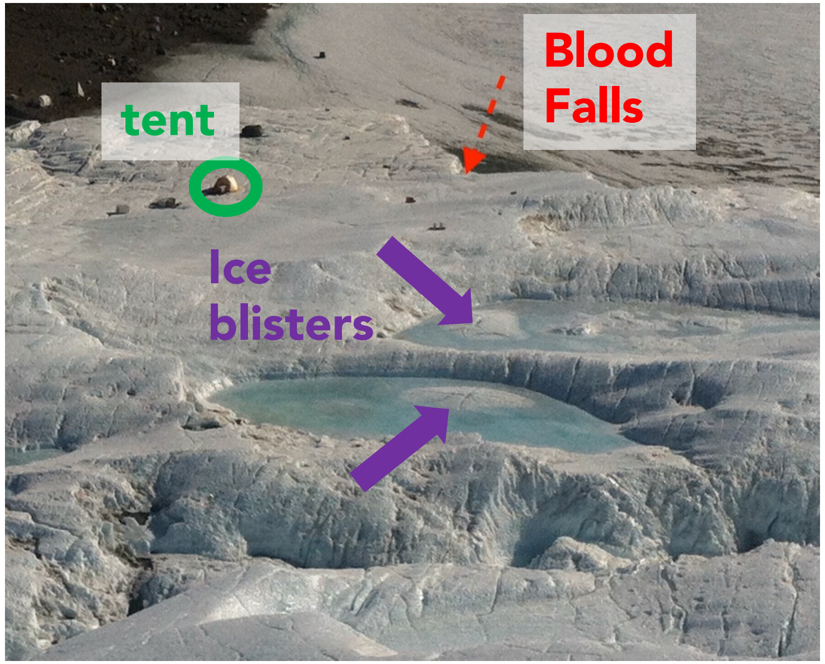
Crack opens 10 cm
graph plots crack length = crack depth



Carr et al., in review, JGR-Earth Surface

Crack opens 10 cm
graph plots crack length = crack depth



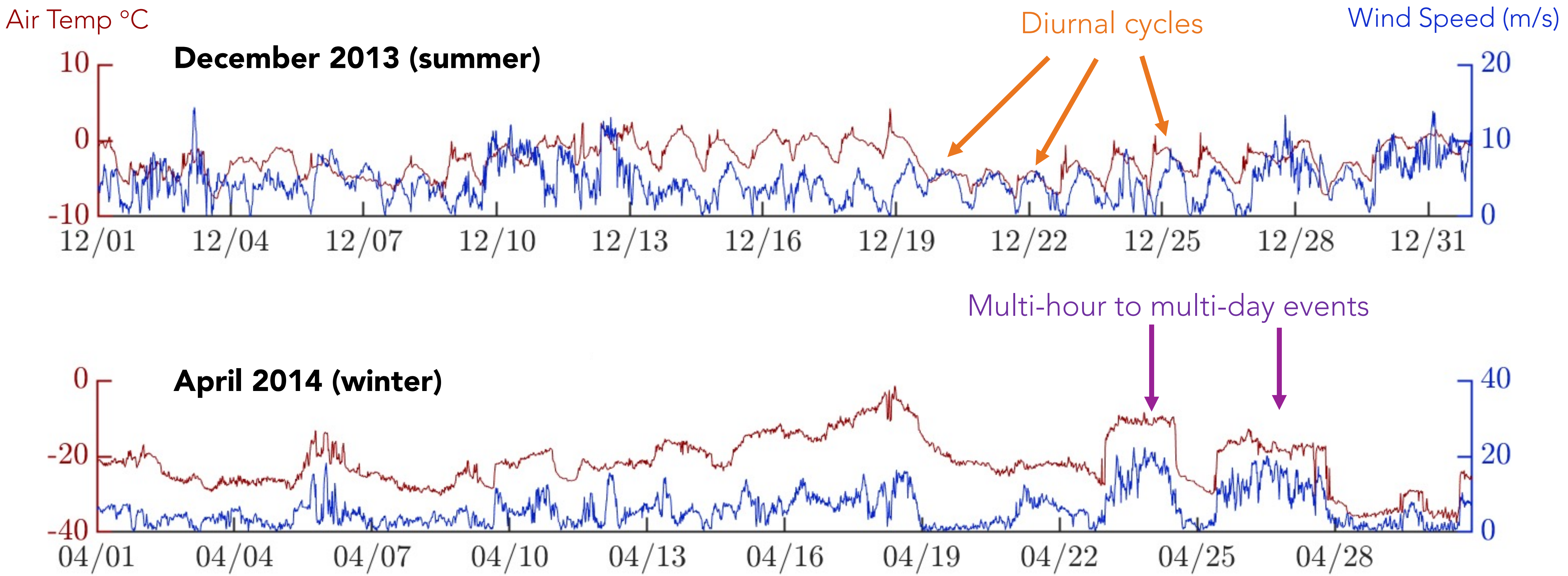


Possible scenario: thermally-driven cracking in the nearby environment masks any clear signal of the Blood Falls crack opening

Photos: Chris Carr

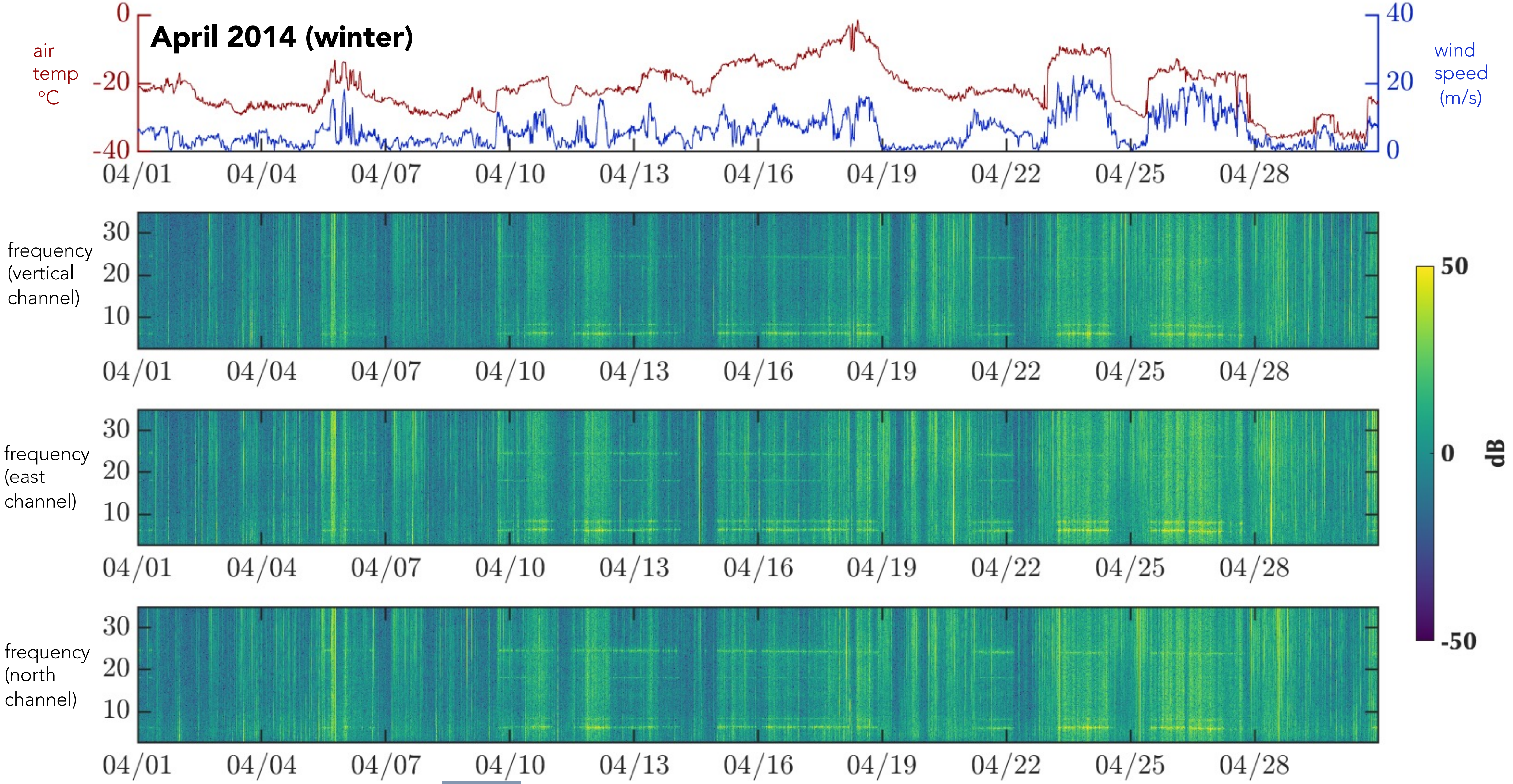
Carr et al., in review, JGR-Earth Surface

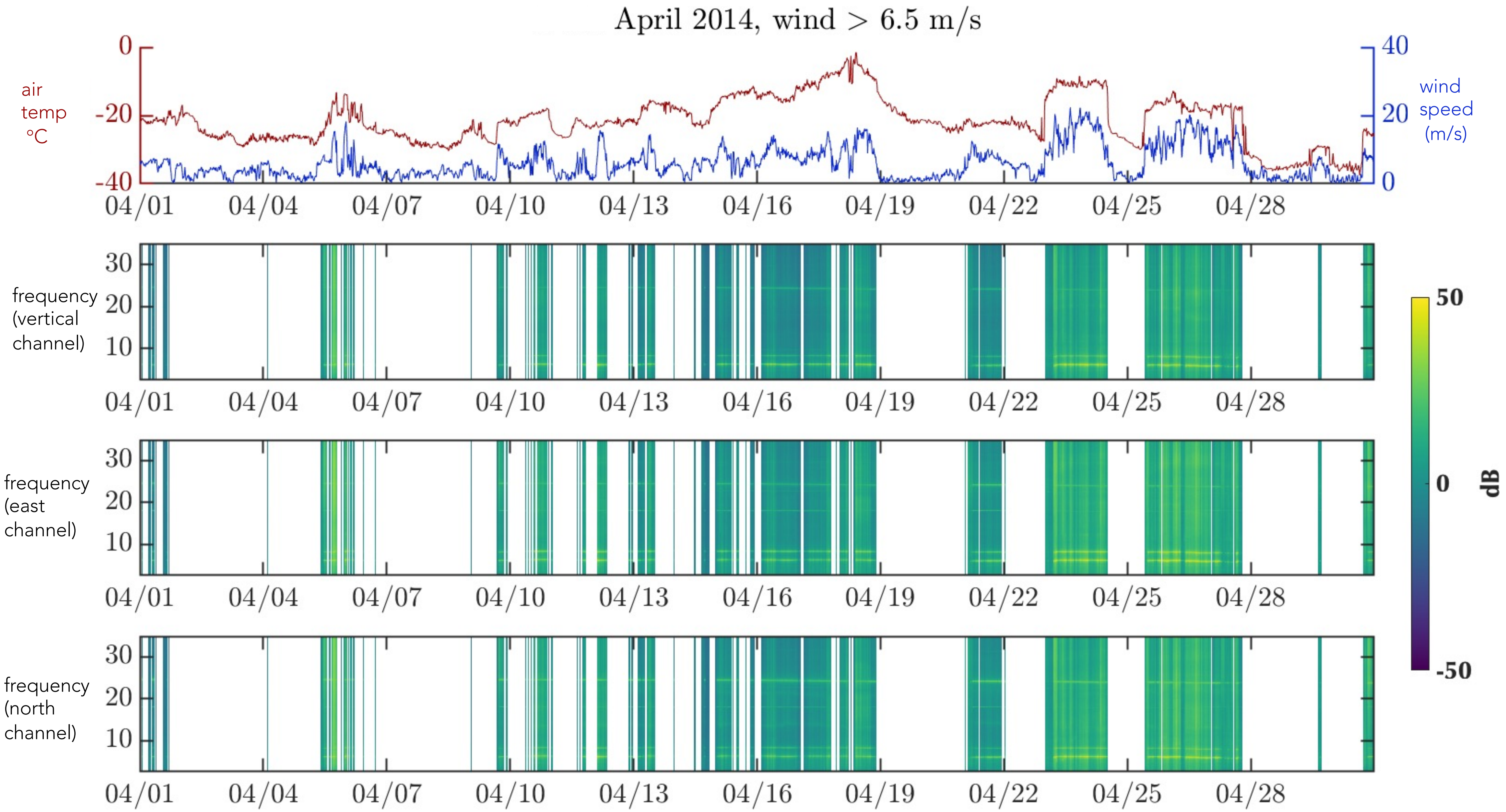
Wind & air temperature strongly related



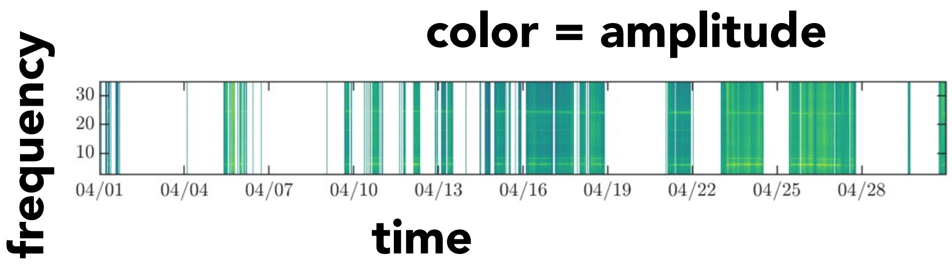
Data: McMurdo Dry Valleys LTER Taylor Glacier Meteorological Station

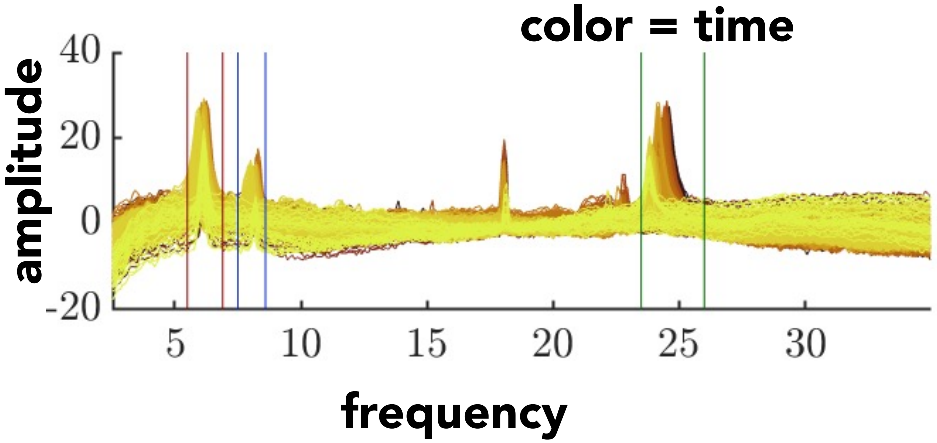
High-energy narrow band features during high wind



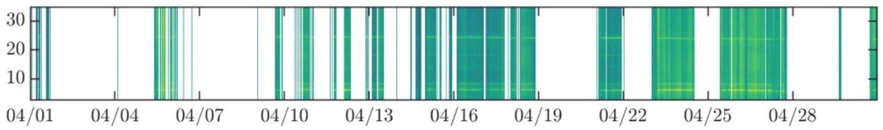


April 2014, wind > 6.5 m/s
air
temp
°C
0
-20
-40
wind
speed
(m/s)
40
20
0
04/01
04/04
04/07
04/10
04/13
04/16
04/19
04/22
04/25
04/28
frequency
(vertical
channel)
frequency
(east
channel)
frequency
(north
channel)
30
20
10
50
0
-50
dB


color = amplitude
frequency
30
20
10
04/01
04/04
04/07
04/10
04/13
04/16
04/19
04/22
04/25
04/28
time


color = time
amplitude
40
20
0
-20
5
10
15
20
25
30
frequency

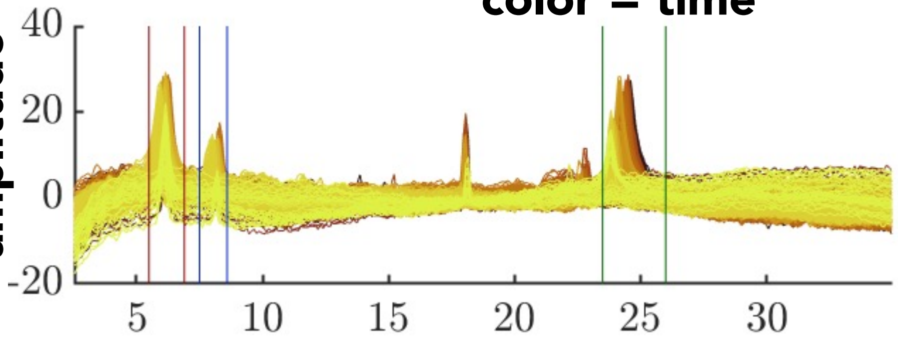
color = amplitude



frequency

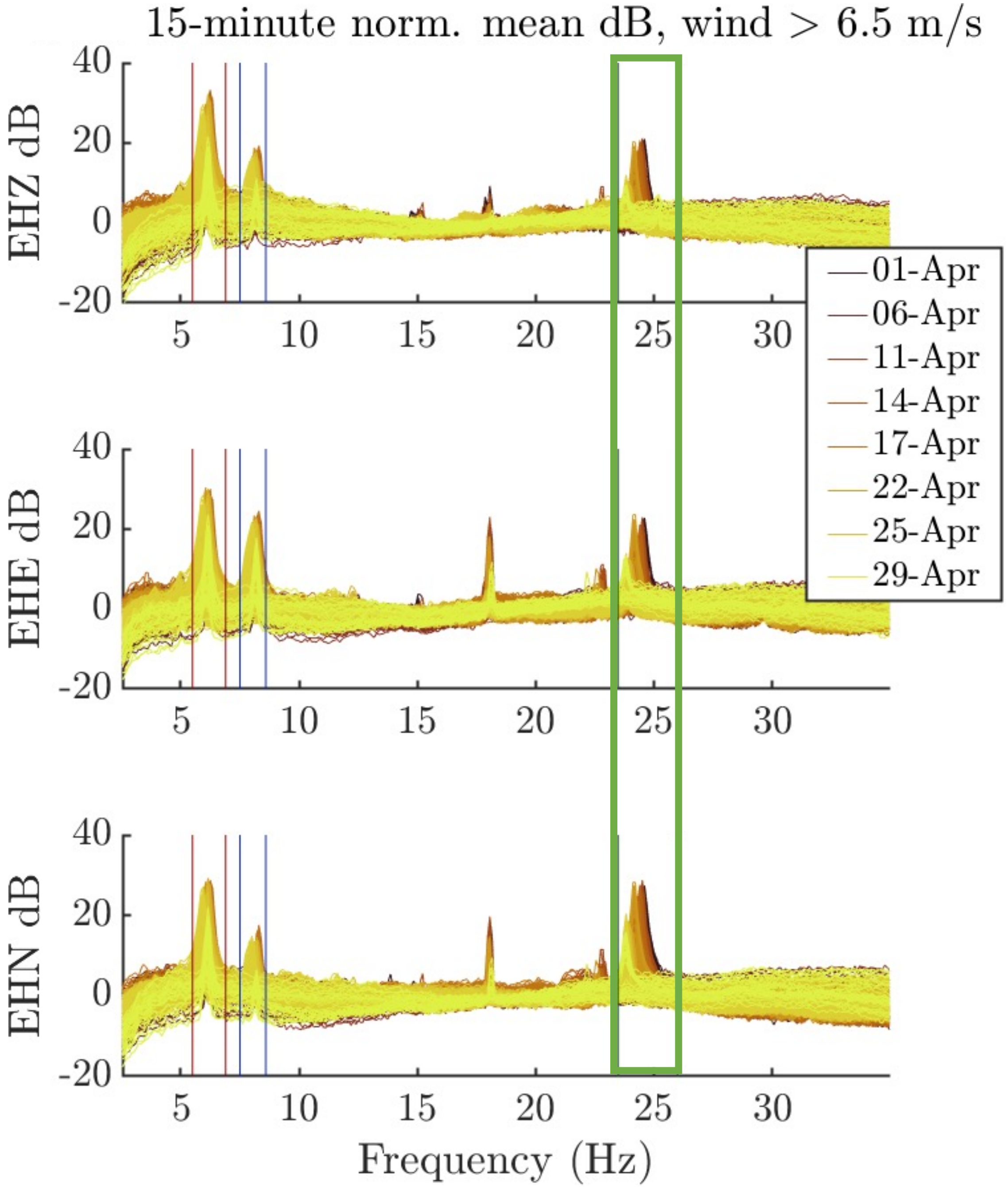
time

color = time



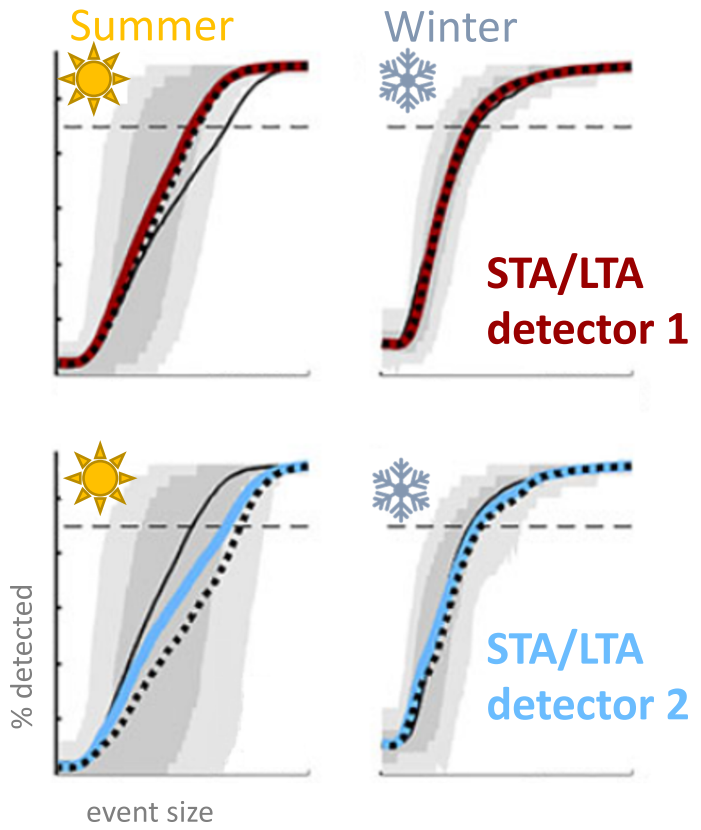
amplitude

frequency



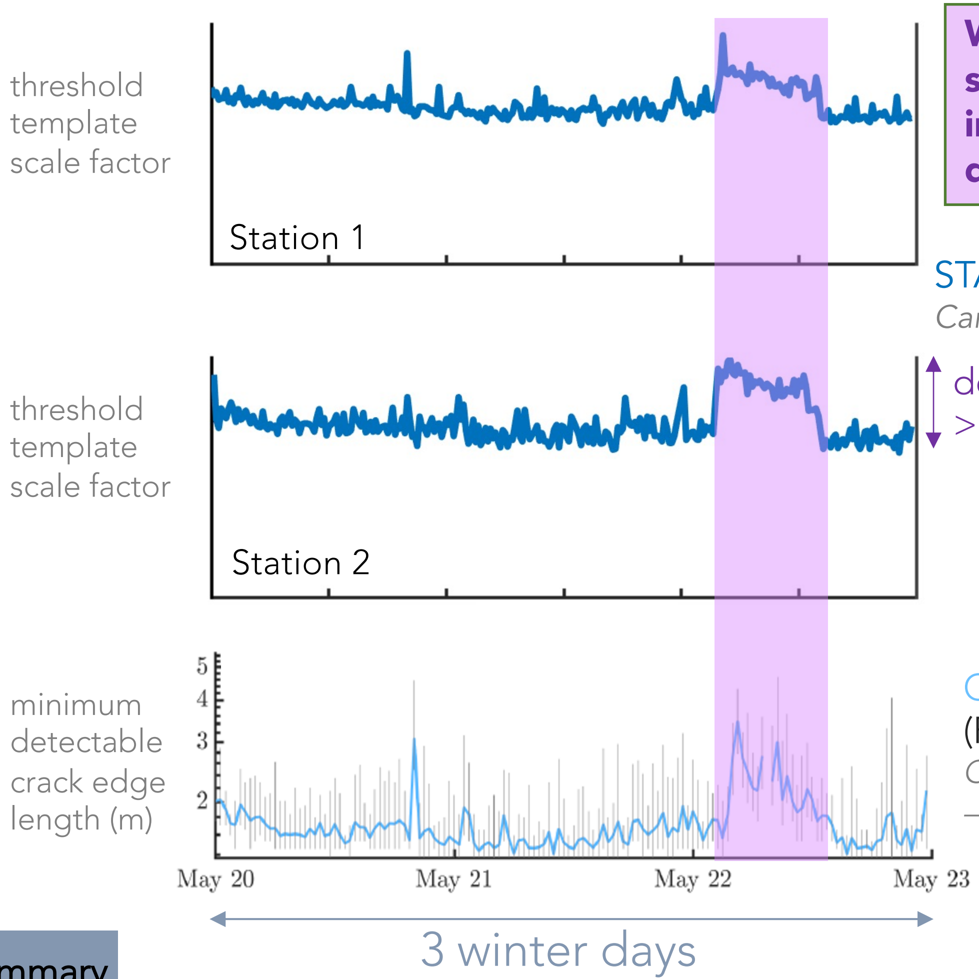
Detector performance varies over different time scales that index noise, interference

1. We observe distinct temporal (seasonal, diurnal) patterns in detector thresholds.



Carr et al., 2020, Journal of Glaciology

2. Weather events can change detector thresholds relative to their baseline seasonal performance



Wind event: sustained increase in minimum detectable event size

STA/LTA detector

Carr et al., 2020, Journal of Glaciology

detection threshold increase: >1 magnitude unit

Correlation detector

(Rayleigh events)

Carr et al., in review, Journal of Geophysics – Earth Surface

Temporal variability in detector performance

- Motivation: Detector performance characterization: **what are the smallest events we can detect?**
- Challenge: **Temporal variability in background noise changes detection thresholds.** Weather-driven microseismicity in the cryosphere is variable and unknown.
- Approach: **Infuse scaled waveforms into real data to measure temporal variability** of detection thresholds, as modulated by environmental microseismicity (general method is signature agnostic).
- Results: Developed an infusion routine, applied to a small high-frequency (~2-40 Hz) Antarctic network, calculated threshold magnitudes for 3 different seismic detectors to **characterize seasonal and diurnal variability**.
- Next Steps: **Develop an automatic infusion routine to enable detection characterization at local distances, including stations near Arctic test sites**. Build capability to routinely integrate threshold estimates informed by meteorological observables.

Questions?

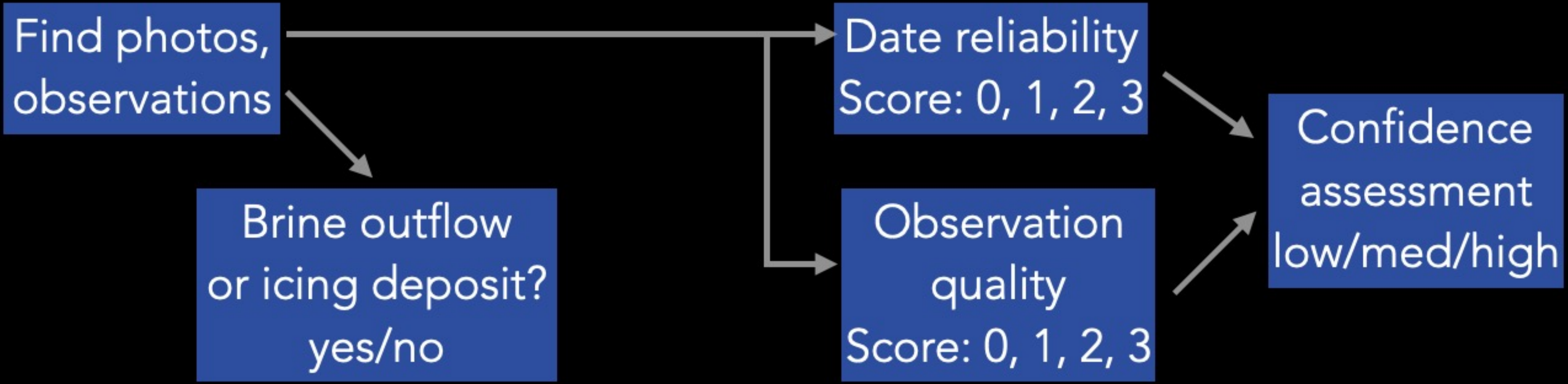
Photo: Chris Carr

Bonus Material : Interpreting the Blood Falls record through historical photos, field observations, and art

Carr, Pettit, & Fountain, in prep, Antarctic Science

FOR EACH SUMMER FIELD SEASON*….

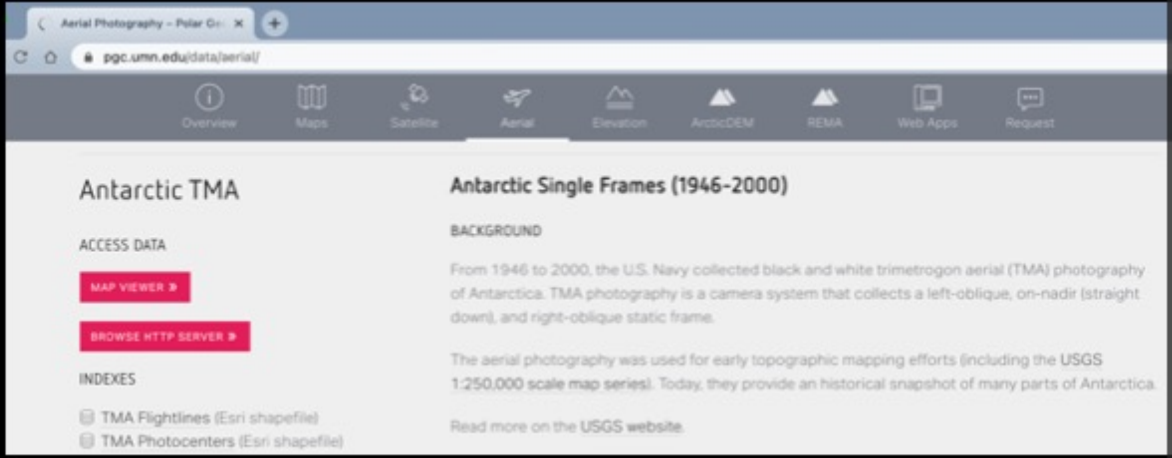
**scope: 1903/04 summer — 1993/94 summer (when records available)*



ONLINE PHOTO ARCHIVES

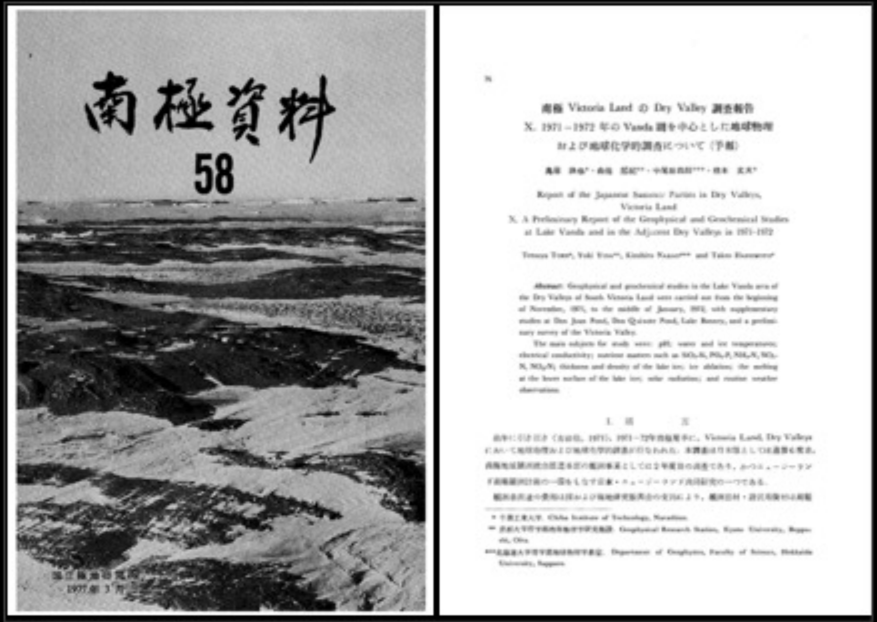
Antarctica New Zealand

McMurdo Dry Valleys Historical Archive



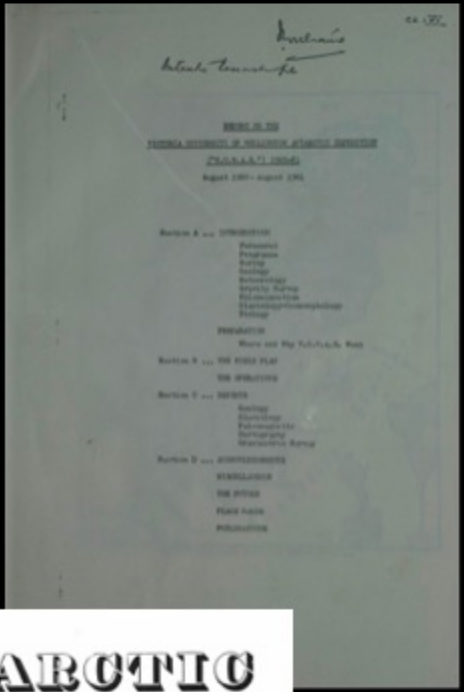
Polar Geospatial Center

REPORTS

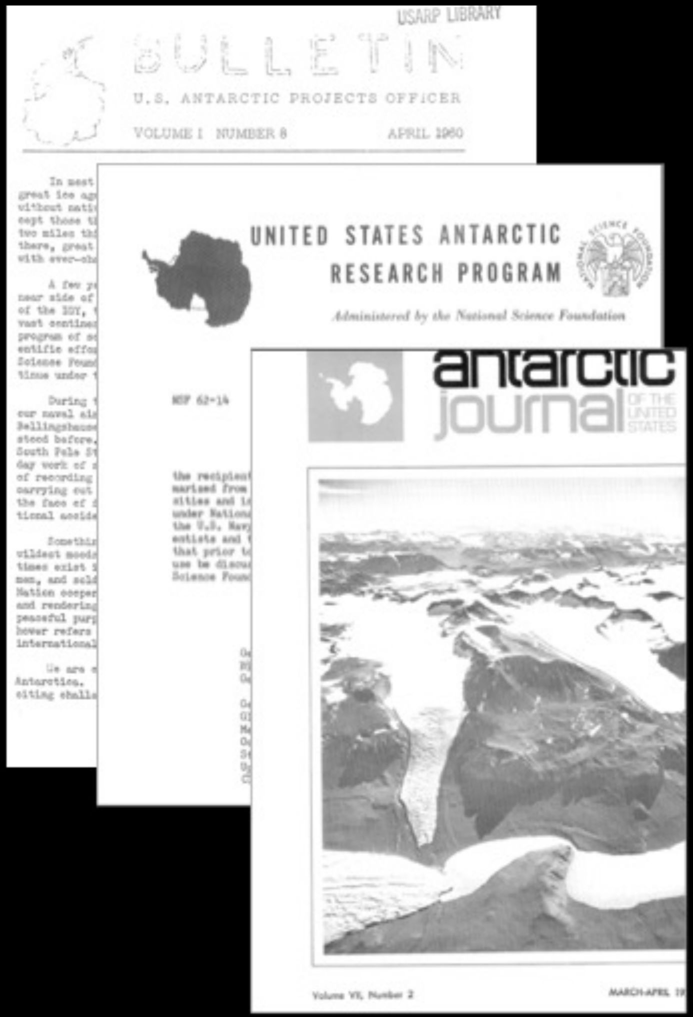


Japan: Antarctic Record

Victoria University of Wellington Antarctic Expedition Reports



New Zealand: Antarctic



Antarctic Journal of the US and predecessors

CONFIDENCE ASSESSMENT FRAMEWORK

Table 2.1: Observation date reliability rating scale

Rating Scale	Selected Examples
0	no reliable date (no date provided, or same photo attributed to many seasons by various sources)
1	date lists single year (1964 vs. 1964-1965), or source dates yield conflicting evidence
2	date of photographer's field season circumstantially determined in this study and does not conflict with other published observations
3	multiple sources agree on date, or published date for single source from original observer

Table 2.2: Observation evidence quality scale

Quality Scale	Selected Examples
0	airphoto taken from too far away or resolution too low
1	written description or field sketch with no mention of presence/absence of Blood Falls high resolution black and white airphotos (icing presence unclear)
2	high resolution black and white airphotos (with icing visible)
3	photo of Blood Falls area, written description of icing deposit over lake ice, written description noting absence of fan

Date reliability			
3	MED	MED	HIGH
2	LOW	MED	MED
1	LOW	LOW	MED
	1	2	3
	Evidence quality		

(Score of 0 = data unclear, no further assessment)

EVIDENCE QUALITY = 1

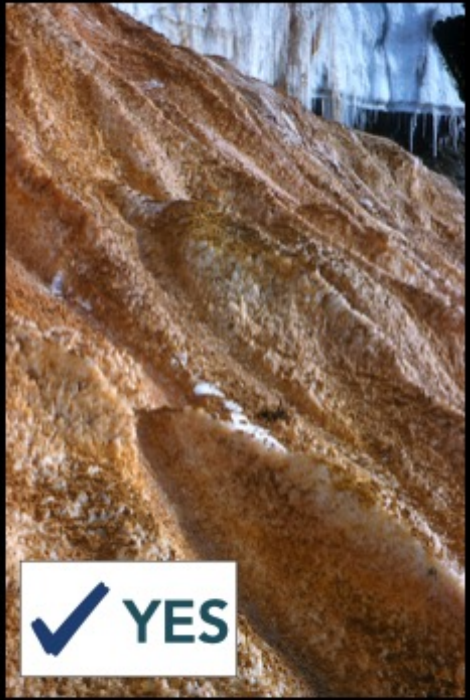
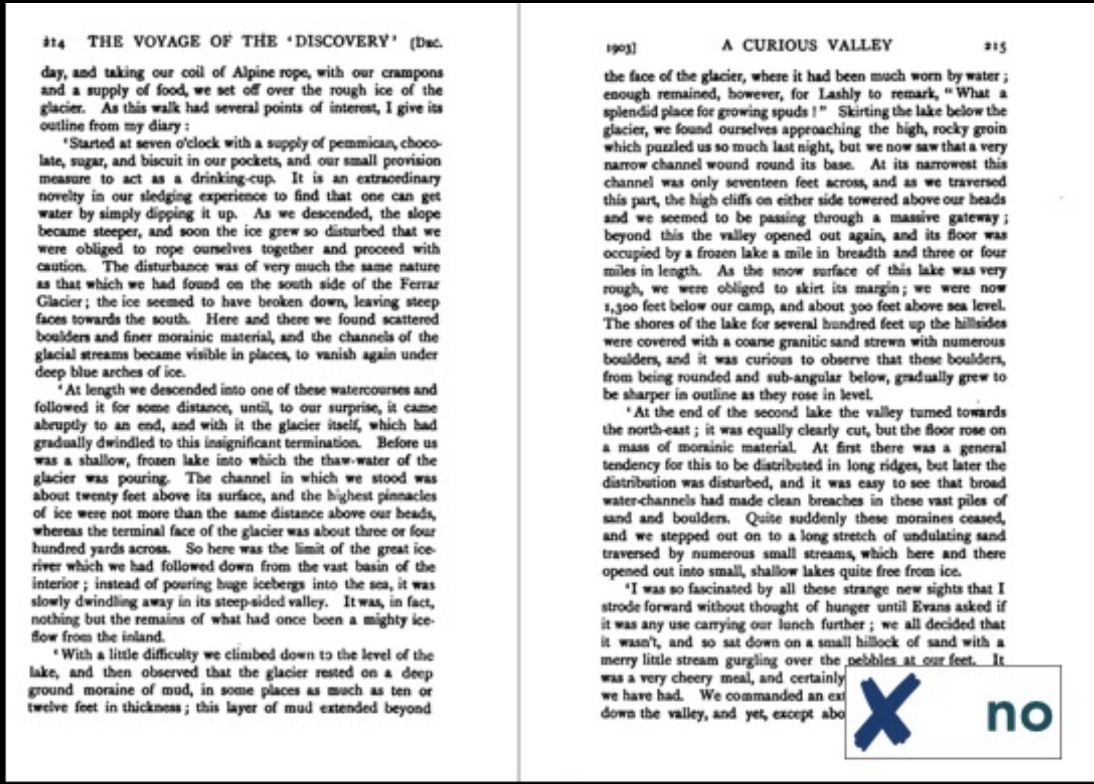


Photo: John McCraw, MDV History Archives

1959-1960 photo,
J. McCraw
(No photo with more context available)

Photo: USGS/PGC

3 Feb. 1981,
Air photo
(Low resolution, icing fan present?)



214 THE VOYAGE OF THE 'DISCOVERY' [Dec.

day, and taking our coil of Alpine rope, with our crampons and a supply of food, we set off over the rough ice of the glacier. As this walk had several points of interest, I give its outline from my diary:

'Started at seven o'clock with a supply of pemmican, chocolate, sugar, and biscuit in our pockets, and our small provision measure to act as a drinking-cup. It is an extraordinary novelty in our sledging experience to find that one can get water by simply dipping it up. As we descended, the slope became steeper, and soon the ice grew so disturbed that we were obliged to rope ourselves together and proceed with caution. The disturbance was of very much the same nature as that which we had found on the south side of the Ferrar Glacier; the ice seemed to have broken down, leaving steep faces towards the south. Here and there we found scattered boulders and finer morainic material, and the channels of the glacial streams became visible in places, to vanish again under deep blue arches of ice.

'At length we descended into one of these watercourses and followed it for some distance, until, to our surprise, it came abruptly to an end, and with it the glacier itself, which had gradually dwindled to this insignificant termination. Before us was a shallow, frozen lake into which the thaw-water of the glacier was pouring. The channel in which we stood was about twenty feet above its surface, and the highest pinnacles of ice were not more than the same distance above our heads, whereas the terminal face of the glacier was about three or four hundred yards across. So here was the limit of the great ice-river which we had followed down from the vast basin of the interior; instead of pouring huge icebergs into the sea, it was slowly dwindling away in its steep-sided valley. It was, in fact, nothing but the remains of what had once been a mighty ice-flow from the inland.

'With a little difficulty we climbed down to the level of the lake, and then observed that the glacier rested on a deep ground moraine of mud, in some places as much as ten or twelve feet in thickness; this layer of mud extended beyond

1903] A CURIOUS VALLEY 215

the face of the glacier, where it had been much worn by water; enough remained, however, for Lashly to remark, "What a splendid place for growing spuds!" Skirting the lake below the glacier, we found ourselves approaching the high, rocky groin which puzzled us so much last night, but we now saw that a very narrow channel wound round its base. At its narrowest this channel was only seventeen feet across, and as we traversed this part, the high cliffs on either side towered above our heads and we seemed to be passing through a massive gateway; beyond this the valley opened out again, and its floor was occupied by a frozen lake a mile in breadth and three or four miles in length. As the snow surface of this lake was very rough, we were obliged to skirt its margin; we were now 1,300 feet below our camp, and about 300 feet above sea level. The shores of the lake for several hundred feet up the hillsides were covered with a coarse granitic sand strewn with numerous boulders, and it was curious to observe that these boulders, from being rounded and sub-angular below, gradually grew to be sharper in outline as they rose in level.

'At the end of the second lake the valley turned towards the north-east; it was equally clearly cut, but the floor rose on a mass of morainic material. At first there was a general tendency for this to be distributed in long ridges, but later the distribution was disturbed, and it was easy to see that broad water-channels had made clean breaches in these vast piles of sand and boulders. Quite suddenly these moraines ceased, and we stepped out on to a long stretch of undulating sand traversed by numerous small streams, which here and there opened out into small, shallow lakes quite free from ice.

'I was so fascinated by all these strange new sights that I strode forward without thought of hunger until Evans asked if it was any use carrying our lunch further; we all decided that it wasn't, and so sat down on a small hillock of sand with a merry little stream gurgling over the pebbles at our feet. It was a very cheery meal, and certainly
we have had. We commanded an ex
down the valley, and yet, except abo

✗ no

18 Dec 1903
R. Scott's description of Taylor terminus area
(no mention of any red discoloration, icing, etc.)

THE
VOYAGE OF
THE 'DISCOVERY'

CAPTAIN ROBERT F. SCOTT

LONDON
SMITH, ELDER, & CO., 15 WATERLOO PLACE

EVIDENCE QUALITY = 3

✓ YES

associated with a saline intrusion of meltwater … the glacier. Surface discharges of salty … terminus of the Taylor Glacier, rich enough in iron oxides to have stained a section of the glacier face red, have been described in detail by *Black* [1969], *Black et al.* [1965], *Black and Bowser* [1968], and *Keys* [1979]. These discharges were so large during the summer of 1990-1991 that by January 1991 reddish-orange slush covered extensive areas of shoreline next to the glacier and was conspicuous from a distance of several kilometers. Water samples collected in the west lobe from depths between 20 and

Spigel & Priscu, 1998

Photo: Fig. 1, Black, 1969

Painting: Jonathan White, Antarctica NZ Archives

Photo: R. Wolak, MDV History Archives

NEWLY REPORTED: 1969-1970

HIGH confidence (date reliability = 3, evidence quality = 3)

Photos: Lois Jones, Byrd Polar and Climate Research Center Archival Program, the Ohio State University

NEWLY REPORTED: 1981-1982

MEDIUM confidence (date reliability = 2, evidence quality = 3)

Photos: Harold Neumann, MDV Archives

Interpreted as a brine release from the lateral site (not the glacier)